Journal of Science in Sport and Exercise (2020) 2:336–348
https://doi.org/10.1007/s42978-020-00067-0

ORIGINAL ARTICLE

Leg Extension Strength, Explosive Strength, Muscle Activation, and Growth as Predictors of Vertical Jump Performance in Youth Athletes

Zachary M. Gillen[1] · Marni E. Shoemaker[1] · Brianna D. McKay[1] · Nicholas A. Bohannon[1] · Sydney M. Gibson[1] · Joel T. Cramer[1]

Received: 25 February 2020 / Accepted: 8 May 2020 / Published online: 22 June 2020

Abstract

Purpose The purpose of this study was to examine the relationships among leg extension strength, explosive strength, muscle activation, and measurements of growth to predictions of vertical jump performance in youth athletes.

Methods Height, body mass, skinfolds, and quadriceps femoris muscle cross-sectional area were measured in 39 sports active children (20 females, 19 males, age = 12.52 ± 0.62 years old). Peak torque (PT), rate of torque development (RTD), rate of velocity development (RVD), and rate of electromyographic amplitude rise (RER) were measured during isometric and isokinetic leg extensions. PT, RTD, and RVD were expressed in absolute terms and normalized to body mass. Estimated jump height (JH) and peak power (PP) were assessed during static (SJ), counter-movement (CMJ), and drop (DJ) jumps.

Results JH exhibited greater correlations with PT normalized to body mass ($r = 0.387–0.758$) than absolute PT ($r = 0.338–0.417$), whereas PP exhibited greater correlations with absolute PT ($r = 0.368–0.837$). Only negligible to moderate relationships existed between JH and PP across all jumps ($r = 0.053–0.605$). Over 50% of the variability in PP was predicted in 24 of 30 regression models with absolute muscle strength, muscle activation, and measurements of growth, while only 6 of 30 models predicted more than 50% of the variability in JH.

Conclusion Overall, absolute static and dynamic muscle strength, muscle activation, and growth better explained PP measured during vertical jumps than estimated JH.

Keywords Children · Adolescent · Torque · Jump height · Power

Introduction

Vertical jump tests are among the most popular assessments of lower-body power for children and adolescents [12, 32]. Perhaps the most popular vertical jump test is the counter-movement jump (CMJ), which involves a downward, eccentric movement followed by a rapid, maximal vertical jump. Other techniques, such as the static jump (SJ) and drop jump (DJ) have also been studied to understand the contributions of the concentric and eccentric phases of the vertical jump in children [1, 11, 32]. Regardless of the technique used, vertical jump performance increases as children grow and develop [9, 10, 19, 20]. Thus, understanding the underlying mechanisms contributing to increases in vertical jump performance may provide unique insight into changes in muscle function during growth and development.

In adults, previous studies have suggested that measurements of isometric or isokinetic leg extension muscle strength may predict vertical jump performance [5, 6, 29, 30, 33]. These studies collectively concluded that muscle strength during leg extension muscle actions is related to, and contributes to predictions of, vertical jump performance in adults. However, we are aware of only two studies examining the relationships among isometric or isokinetic leg extension strength and vertical jump performance in children and adolescents [21, 27]. Rouis et al. [27] measured isokinetic leg extension strength at angular velocities of 90, 180, 240, and 300°/s and vertical jump height (JH) during the CMJ in adolescent females. The authors concluded that

✉ Joel T. Cramer
jcramer@unl.edu

[1] Department of Nutrition and Health Sciences, University of Nebraska-Lincoln, 211 Ruth Leverton Hall, Lincoln, NE 68583, USA

isokinetic strength at high angular velocities (> 240°/s) was strongly related to JH. McKinlay et al. [21] examined the relationships among isometric and isokinetic (angular velocity = 240°/s) leg extension strength and estimated JH from the SJ, CMJ, and DJ in adolescent males. The authors concluded that isokinetic, but not isometric, strength was significantly related to estimated JH from the CMJ. Furthermore, McKinlay et al. [21] reported that isokinetic leg extension strength and body mass consistently contributed to regression models predicting estimated JH from the SJ, CMJ, and DJ. Interestingly, both Rouis et al. [27] and McKinlay et al. [21] found that when muscle strength was normalized to body mass, the magnitudes of relationships between strength and JH increased, regardless of the angular velocity during the leg extension muscle action. The fact that body mass was a confounding factor in the relationships among strength and JH in young males and females [21, 27] was consistent with several previous studies in adults [17, 24, 33, 36].

Using regression analyses, McKinlay et al. [21] reported that isokinetic leg extension strength at an angular velocity of 240°/s and body mass together predicted 32%–44% of the variance in estimated JH during the SJ and CMJ. Similarly, Rouis et al. [27] found that isokinetic leg extension strength from angular velocities of 180–300°/s predicted 46%–72% of the variance in JH. Previous studies in adults [5, 6, 26, 29, 30, 33, 34] have found that isometric and isokinetic strength, with angular velocities ranging from 60–180°/s, predicted 16%–74% of the variance in JH. However, since the vertical jump test is considered to be an assessment of lower-body peak power (PP), measurements of PP from vertical ground reaction forces should be included in addition to JH. We are unaware of any previous studies in children and adolescents to predict vertical jump performance, quantified as both JH and PP, from isometric and isokinetic leg extension muscle actions across the velocity spectrum, as well as growth measurements. Therefore, the purposes of this study were (a) to examine the relationships among leg extension strength, explosive strength, muscle activation, growth, and vertical jump performance assessed by estimated JH and PP, and (b) explore the contributions of leg extension strength, explosive strength, muscle activation, and growth to the prediction of estimated JH and measured PP during the SJ, CMJ, and DJs in youth athletes.

Methods

Thirty-nine youth athletes (SD age = 12.5 ± 0.6 y, maturity offset = − 0.44 ± 0.57 y, height = 156.3 ± 3.93 cm, body mass = 52.6 ± 5.24 kg) participated in this study. All participants reported participating in one or more sports for one to five hours per week during the year prior to this study. Sports included baseball, basketball, cheerleading, cross-country, football, gymnastics, lacrosse, rugby, soccer, softball, speed/power/agility training, swimming/diving, tennis, track and field, trap shooting, volleyball, weightlifting, and wrestling. The participants and their parent or legal guardian completed the PAR-Q + 2015 [35] and were allowed to participate if questions 1–7 were answered "no" or all of the follow-up questions were answered "no." The present study was approved by the University of Nebraska-Lincoln Institutional Review Board for the protection of human subjects (IRB # 20171017495EP, title: Changes in noninvasive, applied physiological laboratory measurements and field measurements of athletic performance in children and youth: Influences of growth and development). Each participant signed the approved assent form if they were 7–18 years old, while 5- and 6-years old verbally assented after being read an age-appropriate assent script. One parent or legal guardian signed the approved consent form.

A cross-sectional design was used for this study. Participants visited the laboratory twice, once for familiarization and once for the experimental trial. Anthropometric and body composition assessments were performed at each trial. During each visit, participants performed in random order three static jumps (SJs), counter-movement jumps (CMJs), and drop jumps (DJs) of three different drop heights: 20, 30, and 40 cm (DJ20, DJ30, and DJ40, respectively). Prior to completing these attempts, each participant performed a general warm-up consisting of squats and lunges, as well as practice attempts of each jump. Participants also performed two, 4-s maximal voluntary isometric contractions (MVICs) of the right leg extensors and three maximal voluntary isokinetic leg extensions at 60, 120, 180, 240, and 300°/s in random order. Prior to the MVICs and maximal isokinetic leg extensions, each participant performed 3-s warm-up isometric leg extension muscle actions at 50% and 75% of perceived effort with 30-s rest between each muscle action. Two to 7 days after the familiarization trial, participants completed the experimental trial. The familiarization trial was performed to allow participants to experience and practice interacting with the testing equipment and procedures [7]. Only data from the experimental trial have been reported herein. Variables calculated during each jump included PP (W) and estimated JH (cm). Variables calculated during the MVICs included peak torque (PT, N·m), peak rate of torque development (RTD, N·m/s), and rate of electromyographic rise (RER, μV_{RMS}/s), while variables calculated during each isokinetic muscle action included PT, peak rate of velocity development (RVD, °/s/s), and RER.

Height (cm), seated height (cm), and body mass (kg) were measured using a digital scale and stadiometer (Seca 769, Hamburg, Germany). These variables were used to estimate maturity offset from peak height velocity using the Mirwald equation [22].

All leg extension muscle actions were completed on a calibrated isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Inc., Shirley, NY, USA) that was custom fitted with a load cell (Omegadyne, model LCHD-500, 0–500 s, Stamford, CT, USA) located between the shin pad and the lever arm. Recorded force (N) was multiplied by the lever arm length (m) to provide torque (N·m). Participants were seated with restraining straps over the pelvis, trunk, and contralateral thigh. The lateral condyle of the femur was aligned with the axis of rotation of the dynamometer head. All MVIC measurements were performed at a leg flexion angle of 60° below the horizontal plane. Participants were instructed to push against the lever arm as hard and fast as possible, while strong verbal encouragement was provided. Following the MVICs, the range of motion for the isokinetic muscle actions was set from 180° to 90°, with 180° representing full leg extension. Each participant was instructed to extend their leg as hard and fast as possible, while strong verbal encouragement was provided.

Ground reaction forces during each vertical jump test were collected using two force plates (PASCO PS-2142, PASCO Scientific, Roseville, CA) seated in a custom platform. To perform the SJ, participants began with their feet in the middle of each force plate and their knees and hips flexed into a static squat position with a knee angle of 90°, using the Original Step (F1005, Marietta, GA) as a guide. From this position, participants performed a maximal vertical jump without a counter-movement. To perform the CMJ, participants began standing in an upright position with their feet in the middle of the force plates and their legs and hips extended. Participants then performed a rapid counter-movement of self-selected depth followed by a maximal vertical jump. To perform the DJ, the Original Step was used to achieve each drop height (20, 30, and 40 cm). Participants began by standing on top of the step and were instructed to drop off the step, land with their feet in the middle of each force plate, and perform a maximal rebound vertical jump as fast as they could upon landing. For all jump conditions, participants were required to keep their hands on their hips.

During all isometric and isokinetic leg extension muscle actions, surface electromyographic signals were recorded from the vastus lateralis muscle with pre-amplified, active electrodes (TSD150B, Biopac Systems, Inc., Santa Barbara, CA) with a center-to-center interelectrode distance of 20 mm, gain of 330 (nominal), input impedance of 100 MΩ, common mode rejection ratio of 95 dB (nominal), and bandwidth of 12–500 Hz. The center of the electrode pair was placed at 66% of the distance between the anterior superior iliac spine and lateral border of the patella [13]. The longitudinal axis of the electrode was arranged parallel to the angle of pennation of the muscle fibers (20°) [16]. A reference electrode (EL503, Biopac Systems Inc., Santa Barbara, CA) was placed over the tibial tuberosity. Placement sites for electromyographic electrodes were shaved and cleaned with isopropyl alcohol prior to application.

During the isometric and isokinetic muscle actions, the position (°) and velocity (°/s) signals were sampled from the isokinetic dynamometer, while torque (N·m) and electromyographic (μV) signals were recorded simultaneously at 1 kHz with a Biopac data acquisition system (MP150, Biopac Systems, Inc., Santa Barbara, CA). The calculations of isometric and isokinetic PT [11, 15], isometric RTD [11], isokinetic RVD [15], and isometric and isokinetic RER [14] used in the present study have been described in detail previously. Isometric PT and RTD, as well as isokinetic RVD were expressed as absolute (N·m, N·m/s, and °/s/s respectively) and body mass normalized (N·m/kg, N·m/s/kg, and °/s/s/kg respectively) values. During all vertical jumps, the *y*-axis, vertical ground reaction forces were sampled at 1 kHz using PASCO Capstone software (PASCO Scientific, Roseville, CA). The raw force–time signals were used for all subsequent analyses. For the SJ, CMJ, and DJs, descriptions for calculations of PP [11] and estimated JH using the flight-time method [18] used in the present study have been described in detail previously. All signals were stored on a personal computer and processed off-line with custom written software (LabVIEW v. 17.0, National Instruments, Austin, TX).

All data were assessed for normality with Shapiro-Wilks tests. One-way repeated measures analyses of variance (ANOVAs) (MVIC vs. 60°/s vs. 120°/s vs. 180°/s vs. 240°/s vs. 300°/s) were used to analyze absolute PT, RVD, and RER across leg extension muscle actions, as well as normalized PT and RVD across leg extension muscle actions. One-way repeated measures ANOVAs (SJ vs. CMJ vs. DJ20 vs. DJ30 vs. DJ40) were used to analyze PP and estimated JH across vertical jump conditions. Pearson product moment correlation coefficients evaluated the relationships among variables (Tables 1, 2, and 3). The following qualitative evaluations of the strength of association were made according to Mukaka [23] based on the absolute values of correlation coefficients: 0.90–1.00 = very high, 0.70–0.89 = high, 0.50–0.69 = moderate, 0.30–0.49 = low, and 0.00–0.29 = negligible. Separate stepwise linear regression models with the following variables were entered in accordance with McKinlay et al. [21]: absolute PT, absolute RTD/RVD, RER, body mass, and maturity offset were conducted to explain the variances in vertical jump PP and JH (Tables 2 and 3). All statistical analyses were performed in IBM SPSS v. 25 (Chicago, IL, USA). An alpha level of $P < 0.05$ was considered statistically significant.

Table 1 Pearson product moment correlation coefficients between normalized values for peak torque (PT), rate of torque development (RTD), rate of velocity development (RVD) as well as peak power (PP) and jump height (JH) from the static jump (SJ), counter-movement jump (CMJ), 20 cm drop jump (DJ20), 30 cm DJ (DJ30), and 40 cm DJ (DJ40)

	PT MVIC	PT 60°/s	PT 120°/s	PT 180°/s	PT 240°/s	PT 300°/s	RTD MVIC	RVD 60°/s	RVD 120°/s	RVD 180°/s	RVD 240°/s	RVD 300°/s	PP SJ	PP CMJ	PP DJ20	PP DJ30	PP DJ40	JH SJ	JH CMJ	JH DJ20	JH DJ30	JH DJ40
PT MVIC	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	-	-	-	-	-	-
PT 60°/s	0.663*	-	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PT 120°/s	0.700*	0.806*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PT 180°/s	0.656*	0.758*	0.855*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PT 240°/s	0.607*	0.762*	0.836*	0.881*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
PT 300°/s	0.556*	0.680*	0.794*	0.828*	0.906*	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
RTD MVIC	0.432*	0.390*	0.384*	0.235	0.318*	0.252	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
RVD 60°/s	0.065	0.133	0.006	–0.062	–0.068	− 0.101	− 0.059	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
RVD 120°/s	0.169	0.227	0.316	0.102	0.180	0.150	0.201	0.626*	–	–	–	–	–	–	–	–	–	–	–	–	–	–
RVD 180°/s	0.236	0.272	0.456*	0.328*	0.387*	0.343*	0.218	0.459*	0.555*	–	–	–	–	–	–	–	–	–	–	–	–	–
RVD 240°/s	0.252	0.210	0.354*	0.316*	0.371*	0.306	0.102	0.620*	0.719*	0.678*	–	–	–	–	–	–	–	–	–	–	–	–
RVD 300°/s	0.068	0.084	0.212	0.123	0.193	0.274	0.060	0.566*	0.668*	0.471*	0.684*	–	–	–	–	–	–	–	–	–	–	–
PP SJ	0.111	0.186	0.123	0.262	0.316	0.249	0.149	− 0.480*	− 0.224	− 0.187	− 0.167	− 0.236	–	–	–	–	–	–	–	–	–	–
PP CMJ	0.449*	0.513*	0.516*	0.617*	0.607*	0.607*	0.073	− 0.402*	− 0.224	− 0.172	− 0.152	− 0.058	0.547*	–	–	–	–	–	–	–	–	–
PP DJ20	0.479*	0.561*	0.559*	0.591*	0.618*	0.597*	0.161	− 0.353*	− 0.163	− 0.100	− 0.161	− 0.116	0.537*	0.913*	–	–	–	–	–	–	–	–
PP DJ30	0.454*	0.539*	0.553*	0.611*	0.576*	0.569*	0.132	− 0.347*	− 0.174	− 0.100	− 0.200	− 0.178	0.522*	0.880*	0.965*	–	–	–	–	–	–	–
PP DJ40	0.492*	0.563*	0.594*	0.643*	0.643*	0.626*	0.135	–0.341*	− 0.156	–0.046	–0.142	− 0.161	0.548*	0.889*	0.954*	0.976*	–	–	–	–	–	–
JH SJ	0.470*	0.561*	0.663*	0.656*	0.758*	0.734*	0.178	0.083	0.275	0.378*	0.442*	0.484*	0.287	0.583*	0.576*	0.489*	0.557*	–	–	–	–	–
JH CMJ	0.434*	0.555*	0.672*	0.624*	0.731*	0.726*	0.255	0.038	0.253	0.369*	0.398*	0.498*	0.235	0.605*	0.590*	0.502*	0.559*	0.943*	–	–	–	–
JH DJ20	0.421*	0.510*	0.616*	0.583*	0.635*	0.642*	0.437*	0.180	0.381*	0.476*	0.476*	0.457*	0.057	0.291	0.253	0.223	0.315	0.701*	0.727*	–	–	–
JH DJ30	0.428*	0.500*	0.598*	0.542*	0.625*	0.651*	0.401*	0.179	0.362*	0.448*	0.490*	0.524*	0.053	0.313	0.317*	0.257	0.325*	0.770*	0.815*	0.922*	–	–
JH DJ40	0.387*	0.473*	0.528*	0.511*	0.587*	0.585*	0.312	0.138	0.344*	0.327*	0.501*	0.512*	0.060	0.376*	0.343*	0.252	0.308	0.790*	0.788*	0.845*	0.881*	–

*Indicates significant relationship ($P < 0.05$)

Table 2 Results of the stepwise regression models to predict peak power (PP) from the static jump (SJ), counter-movement jump (CMJ), and drop jumps of 20, 30, and 40 cm (DJ20, DJ30, and DJ40, respectively) from peak torque (PT), rate of torque and velocity development (RTD and RVD, respectively) rate of electromyographic rise (RER) from isometric and isokinetic muscle actions, as well as body mass (BM) and maturity offset (MO)

	MVIC							60°/s							120°/s						
Jump type	Pre-dictor	Pairwise R	β	Std. β	P	r^2	P	Predic-tor	Pairwise R	β	Std. β	P	r^2	P	Predic-tor	Pairwise R	β	Std. β	P	r^2	P
SJ PP	PT	0.368*	0.22	0.015	0.960	***0.180***	***0.007***	PT	0.408*	3.25	0.186	0.473	***0.180***	***0.007***	PT	0.375*	1.55	0.083	0.755	***0.180***	***0.007***
	RTD	0.387*	0.23	0.172	0.422			RVD	− 0.063	− 0.41	− 0.223	0.159			RVD	0.357*	0.27	0.192	0.272		
	RER	0.126	0.05	0.138	0.360			RER	0.193	0.09	0.236	0.116			RER	0.291	0.08	0.259	0.082		
	BM	***0.425****	***16.41***	***0.425***	***0.007***			***BM***	***0.425****	***16.41***	***0.425***	***0.007***			***BM***	***0.425****	***16.41***	***0.425***	***0.007***		
	MO	0.363*	59.19	0.168	0.376			MO	0.363*	59.19	0.168	0.376			MO	0.363*	59.19	0.168	0.376		
CMJ PP	***PT***	***0.738****	***15.36***	***0.738***	**< 0.001**	***0.544***	**< 0.001**	***PT***	***0.765****	***19.08***	***0.765***	**< 0.001**	***0.586***	**< 0.001**	***PT***	***0.782****	***20.80***	***0.782***	**< 0.001**	***0.611***	**< 0.001**
	RTD	0.494*	− 0.35	− 0.186	0.292			RVD	0.300	− 0.48	− 0.184	0.152			RVD	0.615*	0.18	0.089	0.564		
	RER	0.188	0.05	0.087	0.446			RER	0.139	− 0.01	− 0.020	0.854			RER	0.219	− 0.02	− 0.047	0.669		
	BM	0.655*	4.47	0.081	0.712			BM	0.655*	5.35	0.097	0.598			BM	0.655*	2.37	0.043	0.813		
	MO	0.628*	126.65	0.252	0.086			MO	0.628*	98.00	0.195	0.185			MO	0.628*	77.40	0.154	0.293		
DJ20 PP	***PT***	**0.743***	***8.98***	***0.383***	***0.005***	***0.708***	**< 0.001**	***PT***	***0.783****	***16.08***	***0.573***	**< 0.001**	***0.662***	**< 0.001**	***PT***	***0.803****	***24.03***	***0.803***	**< 0.001**	***0.644***	**< 0.001**
	RTD	0.539*	− 0.04	− .019	0.900			RVD	0.307	− 0.22	− 0.076	0.537			RVD	0.659*	0.35	0.156	0.286		
	RER	***0.245***	***0.18***	***0.290***	***0.006***			RER	0.161	0.13	0.200	0.092			RER	0.305	0.02	0.044	0.681		
	BM	0.627*	2.73	0.044	0.819			BM	0.627*	− 3.78	− 0.061	0.722			BM	0.627*	− 5.34	− 0.086	0.622		
	MO	***0.724****	***279.25***	***0.494***	***0.001***			***MO***	***0.724****	***172.63***	***0.305***	***0.028***			MO	0.724*	149.86	0.265	0.054		
DJ30 PP	***PT***	***0.744****	***7.83***	***0.320***	***0.009***	***0.761***	**< 0.001**	***PT***	***0.790****	***14.77***	***0.504***	**< 0.001**	***0.725***	***0.001***	***PT***	***0.816****	***17.34***	***0.555***	**< 0.001**	***0.746***	**< 0.001**
	RTD	0.533*	− 0.07	− 0.030	0.820			RVD	0.306	− 0.02	− 0.007	0.952			RVD	0.665*	0.38	0.162	0.195		
	RER	***0.197***	***0.17***	***0.268***	***0.005***			RER	0.094	0.11	0.163	0.129			RER	0.302	0.04	0.082	0.371		
	BM	0.654*	8.03	0.124	0.467			BM	0.654*	− 0.84	− 0.013	0.935			BM	0.654*	− 4.40	− 0.068	0.648		
	MO	***0.788****	***355.14***	***0.602***	**< 0.001**			***MO***	***0.788****	***249.28***	***0.422***	***0.001***			***MO***	***0.788****	***222.88***	***0.378***	***0.003***		
DJ40 PP	***PT***	***0.728****	***8.32***	***0.317***	***0.010***	***0.756***	**< 0.001**	***PT***	***0.778****	***15.18***	***0.483***	**< 0.001**	***0.722***	**< 0.001**	***PT***	***0.812****	***18.38***	***0.548***	**< 0.001**	***0.750***	**< 0.001**
	RTD	0.511*	− 0.17	− 0.073	0.586			RVD	0.303	− 0.05	− 0.015	0.892			RVD	0.640*	0.37	0.148	0.235		
	RER	***0.145***	***0.17***	***0.251***	***0.008***			RER	0.064	0.12	0.170	0.114			RER	0.280	0.05	0.084	0.356		
	BM	0.634*	1.81	0.026	0.879			BM	0.634*	− 4.52	− 0.065	0.673			BM	0.634*	− 9.73	− 0.140	0.343		
	MO	***0.808****	***383.99***	***0.606***	**< 0.001**			***MO***	***0.808****	***280.08***	***0.442***	***0.001***			***MO***	***0.808****	***245.52***	***0.387***	***0.002***		

	180°/s							240°/s							300°/s						
Jump type	Pre-dictor	Pairwise R	β	Std. β	P	r^2	P	Predic-tor	Pairwise R	β	Std. β	P	r^2	P	Predic-tor	Pairwise R	β	Std. β	P	r^2	P
SJ PP	PT	0.447*	3.08	0.148	0.530	***0.385***	**< 0.001**	***PT***	***0.498****	***12.03***	***0.498***	***0.001***	***0.248***	***0.001***	***PT***	***0.439****	***11.22***	***0.439***	***0.005***	***0.193***	***0.005***
	RVD	0.356*	− 0.19	-0.193	0.316			RVD	0.438*	0.04	0.033	0.907			RVD	0.372*	0.02	0.021	0.940		
	RER	***0.229***	***0.14***	***0.461***	***0.001***			RER	0.162	− 0.001	− 0.002	0.990			RER	0.068	− 0.01	− 0.037	0.809		
	BM	***0.425****	***12.80***	***0.331***	***0.018***			BM	0.425*	3.98	0.103	0.650			BM	0.425*	8.04	0.208	0.394		
	MO	0.363*	38.05	0.108	0.521			MO	0.363*	16.21	0.046	0.818			MO	0.363*	51.08	0.145	0.452		

Table 2 (continued)

Jump type	180°/s Predictor	Pairwise R	β	Std. β	P	r^2	P	240°/s Predictor	Pairwise R	β	Std. β	P	r^2	P	300°/s Predictor	Pairwise R	β	Std. β	P	r^2	P
CMJ PP	***PT***	***0.818****	***24.30***	***0.818***	**< 0.001**	***0.669***	**< 0.001**	***PT***	***0.835****	***28.74***	***0.835***	**< 0.001**	***0.697***	**< 0.001**	***PT***	***0.824****	***30.05***	***0.824***	**< 0.001**	***0.679***	**< 0.001**
	RVD	0.587*	− 0.22	-0.156	0.320			RVD	0.707*	− 0.08	− 0.049	0.788			RVD	0.764*	0.39	0.253	0.247		
	RER	0.259	0.01	0.032	0.749			RER	0.219	− 0.02	− 0.061	0.529			RER	0.219	0.01	0.026	0.788		
	BM	0.655*	− 2.15	-0.039	0.815			BM	0.655*	1.93	0.035	0.809			BM	0.655*	0.77	0.014	0.930		
	MO	0.628*	42.22	0.084	0.542			MO	0.628*	57.29	0.114	0.361			MO	0.628*	92.47	0.184	0.125		
DJ20 PP	***PT***	***0.804****	***26.88***	***0.804***	**< 0.001**	***0.647***	**< 0.001**	***PT***	***0.837****	***26.29***	***0.679***	**< 0.001**	***0.737***	**< 0.001**	***PT***	***0.821****	***26.33***	***0.642***	**< 0.001**	***0.738***	**< 0.001**
	RVD	0.627*	− 0.03	-0.021	0.896			RVD	0.677*	− 0.23	− 0.132	0.444			RVD	0.720*	0.48	0.281	0.079		
	RER	0.287	0.03	0.066	0.524			RER	0.209	0.00	− 0.005	0.959			RER	0.172	0.04	0.081	0.392		
	BM	0.627*	− 5.09	-0.082	0.636			BM	0.627*	− 5.46	− 0.088	0.525			BM	0.627*	− 9.62	− 0.155	0.283		
	MO	0.724*	141.38	0.250	0.074			***MO***	***0.724****	***134.61***	***0.238***	***0.048***			***MO***	***0.724****	***167.79***	***0.297***	***0.010***		
DJ30 PP	***PT***	***0.829****	***20.33***	***0.583***	**< 0.001**	***0.755***	**< 0.001**	***PT***	***0.819****	***22.90***	***0.567***	**< 0.001**	***0.764***	**< 0.001**	***PT***	***0.809****	***23.87***	***0.557***	**< 0.001**	***0.780***	**< 0.001**
	RVD	0.637*	− 0.05	-0.031	0.822			RVD	0.666*	− 0.18	− 0.097	0.553			RVD	0.688*	0.45	0.251	0.087		
	RER	0.292	0.03	0.062	0.477			RER	0.126	− 0.03	− 0.061	0.512			RER	0.130	0.03	0.071	0.414		
	BM	0.654*	− 5.18	− 0.080	0.581			BM	0.654*	− 0.97	− 0.015	0.907			BM	0.654*	− 5.83	− 0.090	0.499		
	MO	***0.788****	***206.63***	***0.350***	***0.005***			***MO***	***0.788****	***226.68***	***0.384***	***0.001***			***MO***	***0.788****	***247.46***	***0.419***	**< 0.001**		
DJ40 PP	***PT***	***0.816****	***21.43***	***0.572***	**< 0.001**	***0.757***	**< 0.001**	***PT***	***0.825****	***26.01***	***0.599***	**< 0.001**	***0.792***	**< 0.001**	***PT***	***0.804****	***26.67***	***0.580***	**< 0.001**	***0.803***	**< 0.001**
	RVD	0.630*	0.03	0.019	0.888			RVD	0.656*	− 0.24	− 0.122	0.426			RVD	0.646*	0.27	0.139	0.322		
	RER	0.240	0.01	0.027	0.757			RER	0.135	− 0.01	− 0.022	0.800			RER	0.074	0.02	0.039	0.639		
	BM	0.634*	− 10.22	− 0.147	0.307			BM	0.634*	− 7.71	− 0.111	0.365			BM	0.634*	− 13.14	− 0.189	0.128		
	MO	***0.808****	***229.66***	***0.362***	***0.004***			***MO***	***0.808****	***232.30***	***0.367***	***0.001***			***MO***	***0.808****	***259.82***	***0.410***	**< 0.001**		

*Indicates significant pairwise correlation. Bold and italicized variables were included in the regression model

Table 3 Results of the stepwise regression models to predict jump height (JH) from the static jump (SJ), counter-movement jump (CMJ), and drop jumps of 20, 30, and 40 cm (DJ20, DJ30, and DJ40, respectively) from peak torque (PT), rate of torque and velocity development (RTD and RVD, respectively) rate of electromyographic rise (RER) from isometric and isokinetic muscle actions, as well as body mass (BM) and maturity offset (MO)

	MVIC							60°/s							120°/s						
Jump type	Predictor Predictor	Pairwise R	β	Std. β	P	r^2	P	Predictor	Pairwise R	β	Std. β	P	r^2	P	Predictor	Pairwise R	β	Std. β	P	r^2	P
SJ JH	PT	0.260	− 0.001	− 0.007	0.974	***0.318***	***0.001***	PT	0.307	− 0.01	− 0.075	0.746	***0.297***	***0.002***	PT	0.399*	0.04	0.205	0.359	***0.172***	***0.009***
	RTD	0.148	− 0.0005	− 0.040	0.804			RVD	0.140	− 0.004	− 0.212	0.205			***RVD***	***0.415****	***0.005***	***0.415***	***0.009***		
	RER	***0.287***	***0.002***	***0.534***	**< 0.001**			***RER***	***0.442****	***0.002***	***0.523***	***0.001***			RER	0.395*	0.001	0.237	0.194		
	BM	− 0.015	− 0.10	− 0.275	0.114			BM	− 0.015	− 0.09	− 0.259	0.143			BM	− 0.015	− 0.11	− 0.300	0.083		
	MO	***0.202***	***0.95***	***0.288***	***0.046***			***MO***	***0.202***	***1.09***	***0.330***	***0.028***			MO	0.202	− 0.03	− 0.010	0.957		
CMJ JH	PT	0.266	0.001	0.009	0.965	***0.224***	***0.010***	PT	0.302	− 0.02	− 0.124	0.119	***0.323***	***0.001***	***PT***	***0.417****	***0.21***	***1.258***	**< 0.001**	***0.532***	**< 0.001**
	RTD	0.222	0.001	0.056	0.746			RVD	0.111	− 0.004	− 0.269	0.097			RVD	0.401*	− 0.0002	− 0.014	0.938		
	RER	***0.260***	***0.001***	***0.410***	***0.009***			***RER***	***0.437****	***0.002***	***0.529***	***0.001***			RER	0.434*	0.0003	0.123	0.358		
	BM	0.004	− 0.09	− 0.272	0.143			BM	0.004	− 0.09	− 0.270	0.119			***BM***	***0.004***	***− 0.35***	***− 1.026***	**< 0.001**		
	MO	***0.245***	***0.96***	***0.311***	***0.043***			***MO***	***0.245***	***1.15***	***0.375***	***0.012***			MO	0.245	− 1.35	− 0.440	0.792		
DJ20 JH	PT	0.186	–	–	–	–	–	PT	0.230	0.02	0.142	0.352	***0.206***	***0.004***	PT	0.298	0.03	0.174	0.276	***0.186***	***0.006***
	RTD	0.263	–	–	–	–	–	RVD	0.175	− 0.0003	− 0.018	0.915			RVD	0.364*	0.002	0.178	0.327		
	RER	0.171	–	–	–	–	–	***RER***	***0.454****	***0.002***	***0.454***	***0.004***			***RER***	***0.431****	***0.001***	***0.431***	***0.006***		
	BM	− 0.074	–	–	–	–	–	BM	− 0.074	− 0.01	− 0.030	0.840			BM	− 0.074	− 0.04	− 0.109	0.472		
	MO	0.118	–	–	–	–	–	MO	0.118	0.75	0.244	0.107			MO	0.118	0.19	0.063	0.678		
DJ30 JH	PT	0.189	–	–	–	–	–	PT	0.214	0.02	0.126	0.408	***0.199***	***0.004***	PT	0.288	0.03	0.159	0.317	***0.193***	***0.005***
	RTD	0.255	–	–	–	–	–	RVD	0.167	− 0.0004	− 0.023	0.889			RVD	0.346*	0.002	0.145	0.423		
	RER	0.223	–	–	–	–	–	***RER***	***0.446****	***0.002***	***0.446***	***0.004***			***RER***	***0.440****	***0.001***	***0.440***	***0.005***		
	BM	− 0.088	–	–	–	–	–	BM	− 0.088	− 0.02	− 0.045	0.764			BM	− 0.088	− 0.05	− 0.124	0.412		
	MO	0.109	–	–	–	–	–	MO	0.109	0.80	0.233	0.127			MO	0.109	0.18	0.053	0.727		
DJ40 JH	PT	0.157	–	–	–	–	–	PT	0.188	0.02	0.111	0.479	***0.155***	***0.013***	PT	0.237	–	–	–	–	–
	RTD	0.175	-	-	-	-	-	RVD	0.087	− 0.002	− 0.093	0.584			RVD	0.301	-	-	-	-	-
	RER	0.231	-	-	-	-	-	***RER***	***0.394****	***0.001***	***0.394***	***0.013***			RER	0.372*	-	-	-	-	-
	BM	− 0.100	-	-	-	-	-	BM	− 0.100	− 0.02	− 0.063	0.684			BM	− 0.100	-	-	-	-	-
	MO	0.062	-	-	-	-	-	MO	0.062	0.54	0.168	0.286			MO	0.062	-	-	-	-	-

	180°/s							240°/s							300°/s						
Jump type	Predictor	Pairwise R	β	Std. β	P	r^2	P	Predictor	Pairwise R	β	Std. β	P	r^2	P	Predictor	Pairwise R	β	Std. β	P	r^2	P
SJ JH	***PT***	***0.413****	***0.25***	***1.276***	**< 0.001**	***0.543***	**< 0.001**	***PT***	***0.520****	***0.29***	***1.292***	**< 0.001**	***0.687***	**< 0.001**	***PT***	***0.503****	***0.26***	***1.080***	**< 0.001**	***0.743***	**< 0.001**
	RVD	0.379*	0.002	0.215	0.248			RVD	0.343*	0.001	0.100	0.624			***RVD***	***0.495****	***0.004***	***0.368***	***0.024***		
	RER	0.265	0.0004	0.132	0.267			RER	0.524*	0.0002	0.064	0.585			RER	0.467*	0.0001	0.041	0.694		
	BM	***− 0.015***	***− 0.38***	***− 0.106***	**< 0.001**			***BM***	***− 0.015***	***− 0.37***	***− 1.006***	**< 0.001**			***BM***	***− 0.015***	***− 0.41***	***− 1.120***	**< 0.001**		
	MO	0.202	− 0.53	− 0.160	0.332			MO	0.202	− 0.43	− 0.131	0.317			MO	0.202	0.33	0.099	0.414		

Table 3 (continued)

Jump type	180°/s Predictor	Pairwise R	β	Std. β	P	r^2	P	240°/s Predictor	Pairwise R	β	Std. β	P	r^2	P	300°/s Predictor	Pairwise R	β	Std. β	P	r^2	P
CMJ JH	***PT***	***0.403****	***0.22***	***1.197***	**< 0.001**	***0.478***	**< 0.001**	***PT***	***0.506****	***0.26***	***1.221***	**< 0.001**	***0.614***	**< 0.001**	***PT***	***0.503****	***0.22***	***0.978***	**< 0.001**	***0.719***	**< 0.001**
	RVD	0.387*	0.002	0.252	0.205			RVD	0.320*	0.0001	0.012	0.956			***RVD***	***0.519****	***0.004***	***0.446***	***0.010***		
	RER	0.221	0.001	0.198	0.115			RER	0.528*	0.0003	0.112	0.389			RER	0.465*	0.0001	0.038	0.729		
	BM	***0.004***	***− 0.33***	***− 0.973***	**< 0.001**			***BM***	***0.004***	***− 0.32***	***− 0.932***	**< 0.001**			***BM***	***0.004***	***− 0.36***	***− 1.074***	**< 0.001**		
	MO	0.245	− 0.18	− 0.058	0.745			MO	0.245	− 0.13	− 0.041	0.780			MO	0.245	0.58	0.190	0.127		
DJ20 JH	***PT***	***0.296***	***0.19***	***1.068***	**< 0.001**	***0.386***	**< 0.001**	PT	0.364*	0.05	0.250	0.261	***0.186***	***0.006***	PT	0.356*	0.06	0.286	0.069	***0.132***	***0.023***
	RVD	0.337*	0.003	0.342	0.110			RVD	0.345*	0.001	0.152	0.325			RVD	0.321*	0.002	0.222	0.177		
	RER	0.259	0.0004	0.165	0.231			***RER***	***0.431****	***0.001***	***0.431***	***0.006***			***RER***	***0.363****	***0.001***	***0.363***	***0.023***		
	BM	***− 0.074***	***− 0.32***	***− 0.945***	**< 0.001**			BM	− 0.074	− 0.02	− 0.049	0.745			BM	− 0.074	− 0.02	− 0.056	0.721		
	MO	0.118	− 0.50	− 0.162	0.397			MO	0.118	0.38	0.125	0.407			MO	0.118	0.49	0.160	0.305		
DJ30 JH	***PT***	***0.266***	***0.15***	***0.729***	***0.011***	***0.407***	**< 0.001**	PT	0.361*	0.05	0.225	0.141	***0.237***	***0.002***	PT	0.370*	0.07	0.282	0.062	***0.193***	***0.005***
	RVD	***0.332****	***0.004***	***0.391***	***0.008***			RVD	0.352*	0.002	0.146	0.329			RVD	0.399*	0.003	0.281	0.074		
	RER	0.254	0.0003	0.101	0.486			***RER***	***0.487****	***0.001***	***0.487***	***0.002***			***RER***	***0.439****	***0.001***	***0.439***	***0.005***		
	BM	***− 0.088***	***− 0.36***	***− 0.946***	**< 0.001**			BM	− 0.088	− 0.02	− 0.060	0.682			BM	− 0.088	− 0.02	− 0.066	0.662		
	MO	0.109	− 0.42	− 0.123	0.520			MO	0.109	0.40	0.117	0.424			MO	0.109	0.54	0.159	0.290		
DJ40 JH	PT	0.245	–	–	–	–	–	PT	0.339*	0.06	0.250	0.608	***0.125***	***0.027***	PT	0.338*	0.06	0.263	0.093	***0.143***	***0.018***
	RVD	0.222	–	–	–	–	–	RVD	0.254	0.002	0.181	0.258			RVD	0.264	0.003	0.266	0.102		
	RER	0.165	–	–	–	–	–	***RER***	***0.353****	***0.001***	***0.353***	***0.027***			***RER***	***0.378****	***0.001***	***0.378***	***0.018***		
	BM	− 0.100	–	–	–	–	–	BM	− 0.100	− 0.03	− 0.080	0.608			BM	− 0.100	− 0.03	− 0.082	0.599		
	MO	0.062	–	–	–	–	–	MO	0.062	0.22	0.067	0.668			MO	0.062	0.33	0.104	0.502		

* Indicates significant pairwise correlation. Bold and italicized variables were included in the regression model

Results

All data were normally distributed ($P \geq 0.185$). Absolute and normalized PT decreased systematically such that MVIC > 60°/s > 120°/s > 180°/s > 240°/s > 300°/s ($P \leq 0.018$, $\eta^2 \geq 0.218$) (Fig. 1a, b). Absolute and normalized RVD increased up to 180°/s to 120°/s ($P < 0.001$, $\eta^2 \geq 0.514$, Fig. 1c, d). RER generally increased across velocity ($P \leq 0.031$, $\eta^2 \geq 0.162$) (Fig. 1e).

PP during the vertical jumps increased from SJ to CMJ ($P < 0.001$, $\eta^2 = 0.817$), with no further increases ($P \geq 0.969$, $\eta^2 \leq 0.012$) (Fig. 2a). JH increased from SJ to CMJ ($P < 0.001$, $\eta^2 = 0.213$), decreased from CMJ to DJ20 ($P < 0.001$, $\eta^2 = 0.018$), and remained lower than SJ and CMJ at DJ30 and DJ40 ($P \leq 0.020$, $\eta^2 \geq 0.312$) (Fig. 2b).

Pearson product moment correlation coefficients for relationships among outcome measures from leg extension muscle actions, vertical jumps, and growth are presented in Tables 1, 2, and 3. PP from SJ was moderately related to PP from all other vertical jump conditions, while PP among CMJ, DJ20, DJ30, and DJ40 exhibited high and very high relationships with each other (Table 1). JH from SJ and CMJ exhibited low to moderate relationships with PP from CMJ, DJ20, DJ30, and DJ40, while JH from DJs exhibited negligible to low relationships with PP from all vertical jump conditions (Table 1). In general, normalized PT was moderately related to PP (Table 1), while absolute PT was highly related to PP (Table 2). Normalized RVD exhibited negligible to low relationships with PP (Table 1), while absolute RVD and RTD exhibited low to moderate relationships with PP (Table 2).

Normalized PT generally exhibited moderate to high relationships with estimated JH from all vertical jump conditions (Table 1), while absolute PT exhibited only low to moderate relationships with estimated JH (Table 3). Normalized and absolute RVD generally exhibited low to

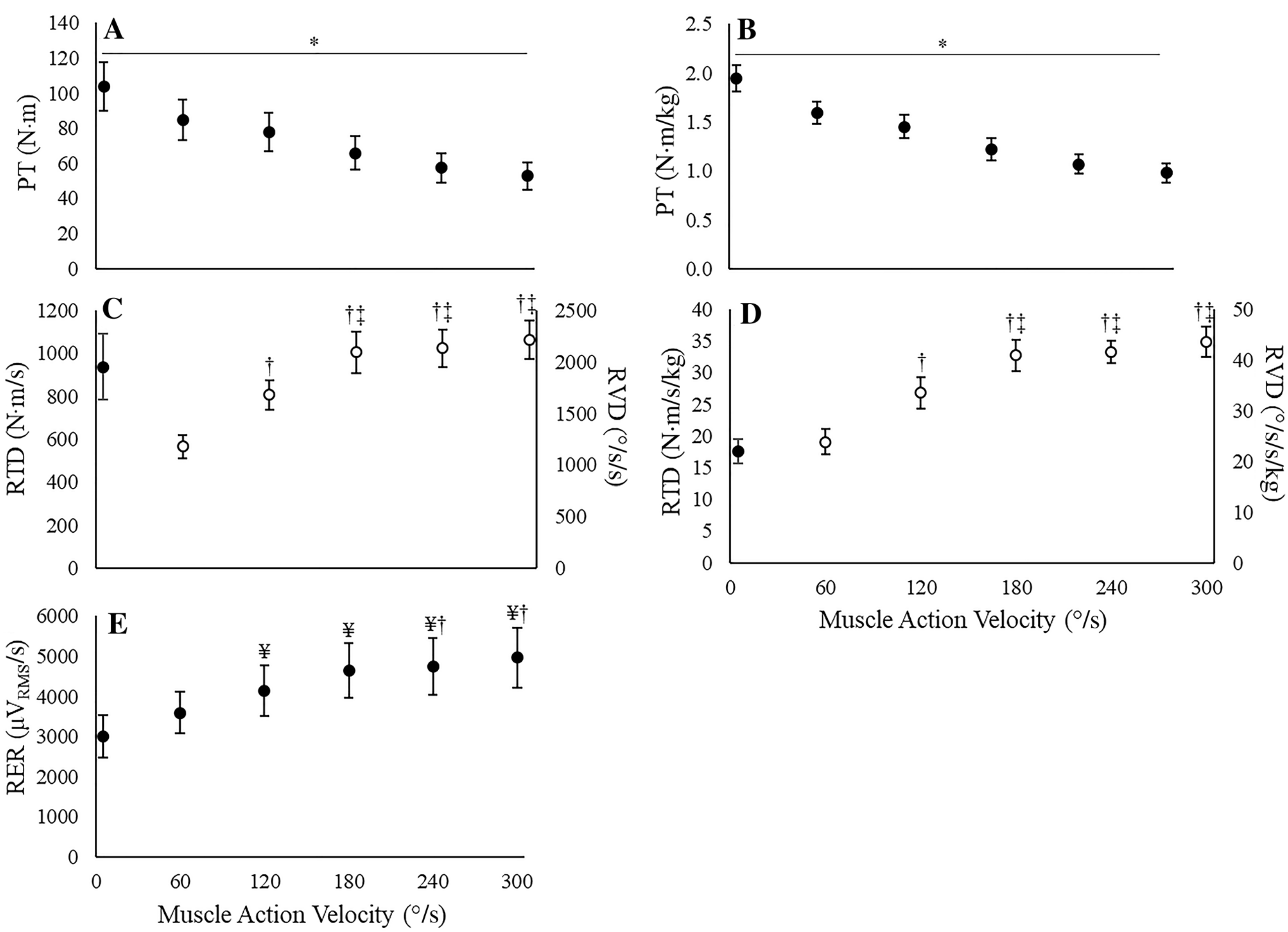

Fig. 1 Means (±95% confidence intervals) for **a** absolute peak torque (PT), **b** normalized PT **c** absolute rate of torque development (RTD) and rate of velocity development (RVD), **d** normalized RTD and RVD, and **e** rate of electromyographic rise (RER) for isometric and isokinetic leg extension muscle actions. For **b** and **c**, closed circle represents RTD during the MVIC, open circles represent RVD during the isokinetic muscle actions. * Indicates systematic decrease across velocities ($P < 0.05$), ¥ greater than isometric muscle action at 0°/s ($P < 0.05$), † indicates greater than 60°/s ($P < 0.05$), ‡ indicates greater than 120°/s ($P < 0.05$)

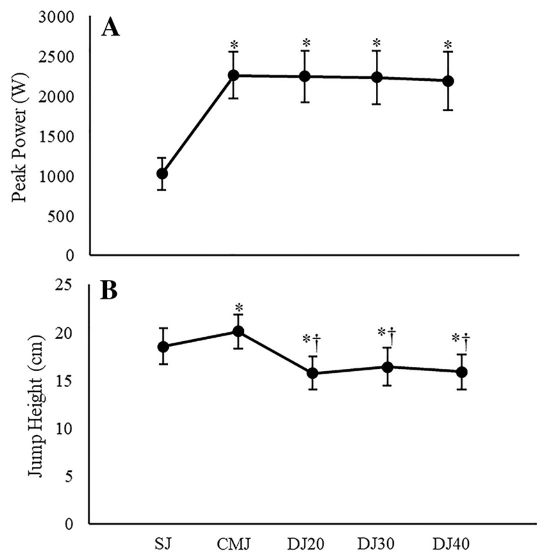

Fig. 2 Means (±95% confidence intervals) for **a** peak power and **b** jump height for the static jump (SJ), counter-movement jump (CMJ), and drop jumps of 20, 30, and 40 cm (DJ20, DJ30, and DJ40, respectively). * Indicates greater than the SJ, † indicates lower than the CMJ

moderate relationships with estimated JH (Tables 1 and 3, respectively).

The results from the regression models predicting PP from all vertical jump conditions are presented in Table 2. Only 18% of the variance in SJ PP was predicted with body mass from the MVIC, 60°/s, and 120°/s models, while 39% of the variance in SJ PP was predicted by RER and body mass at 180°/s. However, with the 240°/s and 300°/s models, 19%–25% of the variance in SJ PP was predicted by isokinetic PT. The 54%–70% of the variance in CMJ PP was predicted by PT, which increased across velocity from MVIC (54%) to 240°/s (70%). When predicting DJ PP, 64%–80% of the variance was predicted by PT and maturity offset.

The results from the regression models predicting JH from all vertical jump conditions are presented in Table 3. The 30%–32% of the variance in SJ JH was predicted with RER and maturity offset from the MVIC and 60°/s models, while only 17% of the variance in SJ JH was predicted with RVD alone from the 120°/s model. The 54%–69% of the variance in SJ JH was predicted with PT and body mass from the 180°/s and 240°/s models, while RVD also contributed to predicting 74% of the variance in SJ JH from the 300°/s model. The 22%–32% of the variance in CMJ JH was predicted by RER and maturity offset from the MVIC and 60°/s models. The 48%–61% of variance in CMJ JH was predicted by PT and body mass in the 120°/s, 180°/s, and 240°/s models, while RVD also contributed to predicting 72% of the variance in the 300°/s model. No variables contributed to predicting DJ20, DJ30, or DJ40 JH from the MVIC models, and no variables from the 120°/s or 180°/s models contributed to predicting DJ40 JH. RER alone predicted 13%–24% of the varaince in DJ JH from the 60°/s, 120°/s, 240°/s, and 300°/s models. PT and body mass predicted 39%–41% of the variance in DJ JH from the 180°/s model.

Discussion

The results of the present study contributed novel and clarifying evidence to the body of literature regarding muscle function in young, athletic males and females. First, relationships among muscle strength, power, and growth differ when vertical jump performance is estimated indirectly with measurements of flight time, rather than direct measurements of power from vertical ground reaction forces. For example, absolute strength exhibited stronger correlations with PP than estimated JH and contributed to 26 out of the 30 regression models predicting PP (Table 2), compared to 9 out of the 30 regression models predicting estimated JH (Table 3). Second, regression models predicting PP had greater predictive indices (r^2) than regression models predicting estimated JH. Specifically, 24 out of the 30 models predicting PP predicted > 50% of the total variance (Table 2), while only 6 out of the 30 models predicting estimated JH predicted > 50% of the total variance (Table 3). Overall, static and dynamic muscle strength, muscle activation, and growth better explained PP measured during the vertical jump than JH estimated from flight time in the present study.

We are aware of only two previous studies among children and adolescents that have quantified the relationships between isometric and/or isokinetic leg extension strength and vertical jump performance [21, 27]. In adolescent females, Rouis et al. [27] reported that PT at 240°/s exhibited a high correlation with JH, while PT at 90°/s, 180°/s, and 300°/s exhibited low to moderate relationships with JH from the CMJ. In pre-adolescent males, McKinlay et al. [21] found that absolute isometric PT exhibited no significant relationships with estimated JH from the SJ, CMJ, or DJ, while absolute isokinetic PT exhibited a low relationship with estimated JH from the CMJ. Similarly, the results of the present study showed that absolute isometric PT exhibited no relationships with estimated JH, while absolute isokinetic PT exhibited low to moderate relationships with estimated JH from SJ, CMJ, and all DJs (Table 3). To extend the results of previous studies [21, 27], the present study showed that measured PP during the SJ exhibited low, but significant, relationships with absolute isometric and isokinetic PT, while PP during the CMJ and all DJs exhibited high relationships with absolute isometric and isokinetic PT (Table 2). Furthermore, absolute PT was included in 26 out of the 30 regression models predicting PP (Table 2), compared to only 9 out of the 30 regression models predicting estimated JH

(Table 3). Based on the standardized β coefficients, which represent the weight and direction of influence of a variable in the models [25], absolute PT was the most influential contributor in 23 out of the 26 models predicting measured PP (Table 2), and 6 out of the 9 models predicting estimated JH (Table 3). Therefore, the correlations and regression models in the present study demonstrated that absolute strength assessed from isometric and/or isokinetic leg extension muscle actions predicts a relatively large proportion of the variance in vertical jump power, but not estimated JH.

Several previous studies in adults have demonstrated that the relationship between strength and JH improves when both isometric and dynamic strength measures are normalized to body mass [17, 24, 33, 36]. In adolescent males and females, McKinlay et al. [21] and Rouis et al. [27] found that normalized measures of isometric and dynamic leg extension strength were more related to JH than absolute strength measures. Similarly, the results of the present study showed that normalizing PT and RTD to body mass increased the magnitudes of relationships between strength and estimated JH (Table 1), while simultaneously decreasing the magnitudes of relationships between strength and measured PP. Furthermore, body mass was included in all 9 of the regression models predicting estimated JH (Table 3) and none of the 26 regression models predicting measured PP (Table 2), all of which included absolute PT. When included as a predictor of estimated JH, body mass influenced the model in the opposite direction of absolute PT (Table 3). That is, based on the standardized β coefficients, absolute PT contributed to the models in the positive direction while body mass contributed in the negative direction. These findings may be explained by rearranging Newton's second law as [24]: acceleration = force ÷ mass. Increasing force while maintaining body mass, decreasing body mass while maintaining force, or both increasing force and decreasing body mass will necessarily increase acceleration and subsequent velocity, thereby improving JH [24]. In the present study, the correlations between normalized strength, PP, and estimated JH, in addition to the simultaneous inclusion of absolute PT and body mass as a predictor of estimated JH and not measured PP, extends the results of previous findings in children and adults [17, 21, 24, 27, 33, 36] that body mass is a confounding factor in the relationship between strength and JH, but not PP.

Previous studies in children and adolescents have reported RTD as a measurement of explosive strength during leg extension muscle actions [4, 8, 21, 31]. However, we are aware of only one study that has examined leg extension RTD in relation to estimated JH in youth athletes [21]. McKinlay et al. [21] reported negligible relationships between absolute and normalized isometric RTD and estimated JH from SJs, CMJs, and DJs. Similarly, in the present study, the relationships between normalized or absolute RTD and estimated JH were low at best (Tables 1 and 3, respectively). In contrast, absolute RTD exhibited low to moderate relationships with PP (Table 2), while the relationships between normalized RTD and PP were negligible (Table 1). However, RTD did not contribute to any regression models predicting estimated JH or PP (Tables 2 and 3). Furthermore, McKinlay et al. [21] suggested that normalized isokinetic RTD was more related to estimated JH than absolute isokinetic RTD. However, previous studies have suggested that RVD, not RTD, should be assessed during isokinetic muscle actions [2, 3, 28]. Due to the lack of studies quantifying isokinetic RVD in youth, further studies are needed to understand if RVD can provide unique insight regarding muscle function during growth and development.

In conclusion, based on the correlations and regression models in the present study, absolute strength was more related to and predicted a large proportion (19%–80%) of the variance in PP (Table 2), but not estimated JH (Table 3). Normalized strength was more related to estimated JH than measured PP (Table 1), while body mass only contributed to the regression models predicting estimated JH (Table 3), not PP (Table 2). Therefore, similar to previous studies [17, 21, 24, 27, 33, 36], body mass confounded the relationships between strength and estimated JH in the present study, while aboslute strength seems to predict a large proportion of the variance in PP. Furthermore, the total variance accounted for when predicting PP (Table 2) was much greater than predictions of estimated JH (Table 3). Finally, despite the fact that RVD did not contribute anything meaningful to our understanding of growth influences on vertical jump performance in the present study, we recommed that future studies assess RVD during isokinetic muscle actions, rather than RTD, to explore whether unique insight can be gained regarding muscle function in youth. Longidutinal studies tracking changes in the underlying mechanisms contributing to vertical jump PP will aid in our understanding of the natural, biological changes in muscle function across growth and development.

Acknowledgements Efforts for this study were funded, in part, by the University of Nebraska Agriculture Research Division with funds provided by the Hatch Act (Agency: U.S. Department of Agriculture, National Institute of Food and Agriculture; Accession No: 1000080; Project No: NEB-36-078) and a grant from Abbott Nutrition, Columbus, OH.

Compliance with ethical standards

Conflict of interest From 2001-present, Dr. Cramer's research has been externally funded by 22 separate project grants from Abbott Nutrition, Nebraska Beef Council, Nebraska Extension, Stepan Lipid Nutrition, Rock Creek Pharmaceuticals, General Nutrition Corporation, Experimental & Applied Sciences, Nutricia, and the University of Nebraska Agriculture Research Division with funds provided by the Hatch Act. From 2010–2013, Joel was an expert witness or expert consultant in 10 separate legal matters representing defendants Vital Pharmaceuticals,

MusclePharm, and Celsius. From 2008–2016, Dr. Joel T. Cramer was a paid consultant for either Abbott Nutrition, General Nutrition Center, ErgoGenix/ErgoPharm, and/or Corr-Jensen Labs. From 2018-present, Joel has served as a paid consultant for Regeneron Pharmaceuticals.

References

1. Bassa E, Patikas D, Panagiotidou A, Papadopoulou S, Pylianidis T, Kotzamanidis C. The effect of dropping height on jumping performance in trained and untrained prepubertal boys and girls. J Strength Cond Res. 2012;26(8):2258–64.
2. Brown LE, Sjostrom T, Comeau MJ, Whitehurst M, Greenwood M, Findley BW. Kinematics of biophysically asymmetric limbs within rate of velocity development. J Strength Cond Res. 2005;19(2):298–301.
3. Brown LE, Whitehurst M, Findley BW. Reliability of rate of velocity development and phase measures on an isokinetic device. J Strength Cond Res. 2005;19(1):189–92.
4. Cohen R, Klentrou P, Gabriel D, Dotan R, Falk B, Mitchell C. Do neuromuscular adaptations occur in endurance-trained boys and men? Appl Physiol Nutr Metab. 2010;35(4):471–9.
5. de Ruiter CJ, Vermeulen G, Toussaint HM, de Haan A. Isometric knee-extensor torque development and jump height in volleyball players. Med Sci Sports Exerc. 2007;39(8):1336–46.
6. de Ruiter CJ, Leeuwen D, Heijblom A, Bobbert MF, de Haan A. Fast unilateral isometric knee extension torque development and bilateral jump height. Med Sci Sports Exerc. 2006;38(10):1843–52.
7. De Ste CM. Advances in paediatric strength assessment: Changing our perspective on strength development. J Sports Sci Med. 2007;6(3):292–304.
8. Dotan R, Mitchell C, Cohen R, Gabriel D, Klentrou P, Falk B. Child–adult differences in the kinetics of torque development. J Sports Sci. 2013;31(9):945–53.
9. Floría P, Harrison AJ. The effect of arm action on the vertical jump performance in children and adult females. J Appl Biomech. 2013;29(6):655–61.
10. Gerodimos V, Zafeiridis A, Perkos S, Dipla K, Manou V, Kellis S. The contribution of stretch-shortening cycle and arm-swing to vertical jumping performance in children, adolescents, and adult basketball players. Pediatr Exerc Sci. 2008;20(4):379–89.
11. Gillen ZM, Jahn JE, Shoemaker ME, McKay BD, Mendez AI, Bohannon NA, Cramer JT. Effects of eccentric pre-loading on concentric vertical jump performance in youth athletes. J Appl Biomech. 2019;35(5):327–35.
12. Gillen ZM, Miramonti AA, McKay BD, Leutzinger TJ, Cramer JT. Test-retest reliability and concurrent validity of athletic performance combine tests in 6–15-year old male athletes. J Strength Cond Res. 2018;32(10):2783–94.
13. Hermens HJ (1999) SENIAM 8: European recommendations for surface electromyography, 2nd edn. Enschede, the Netherlands: Roessingh Research and Development
14. Jenkins NDM, Buckner SL, Cochrane KC, Bergstrom HC, Palmer TB, Johnson GO, Schmidt RJ, Housh TJ, Cramer JT. Age-related differences in rates of torque development and rise in EMG are eliminated by normalization. Exp Gerontol. 2014;57:18–28.
15. Jenkins NDM, Housh TJ, Palmer TB, Cochrane KC, Bergstrom HC, Johnson GO, Schmidt RJ, Cramer JT. Relative differences in strength and power from slow to fast isokinetic velocities may reflect dynapenia. Muscle Nerve. 2015;52(1):120–30.
16. Jenkins ND, Miramonti AA, Hill EC, Smith CM, Cochrane-Snyman KC, Housh TJ, Cramer JT. Greater neural adaptations following high- vs. low-load resistance training. Front Physiol. 2017;8:331.
17. Khamoui A, Brown L, Nguyen D, Uribe B, Coburn J, Noffal G, Tran T. Relationship between force-time and velocity-time characteristics of dynamic and isometric muscle actions. J Strength Cond Res. 2011;25(1):198–204.
18. Linthorne NP. Analysis of standing vertical jumps using a force platform. Am J Phys. 2001;69(11):1198–204.
19. Lloyd R, Oliver J, Hughes M, Williams C. The influence of chronological age on periods of accelerated adaptation of stretch-shortening cycle performance in pre and postpubescent boys. J Strength Cond Res. 2011;25(7):1889–977.
20. Malina R, Eisenmann J, Cumming S, Ribeiro B, Aroso J. Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13–15 years. Eur J Appl Physiol. 2004;91(5–6):555–62.
21. McKinlay BJ, Wallace PJ, Dotan R, Long D, Tokuno C, Gabriel DA, Falk B. Isometric and dynamic strength and neuromuscular attributes as predictors of vertical jump performance in 11- to 13-year-old male athletes. Appl Physiol Nutr Metab. 2017;42(9):924–30.
22. Mirwald RL, Baxter-Jones ADG, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc. 2002;34(4):689–94.
23. Mukaka MM. Statistics corner: a guide to appropriate use of correlation coefficient in medical research. Malawi Med J. 2012;24(3):69–71.
24. Nuzzo J, McBride J, Cormie P, McCaulley G. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J Strength Cond Res. 2008;22(3):699–707.
25. Pedhazur EJ. Multiple regression in behavioral research. 3rd ed. Fort Worth: Harcourt Brace College Publ; 1997.
26. Pua Y, Koh MT, Teo Y. Effects of allometric scaling and isokinetic testing methods on the relationship between countermovement jump and quadriceps torque and power. J Sports Sci. 2006;24(4):423–32.
27. Rouis M, Coudrat L, Jaafar H, Filliard J, Vandewalle H, Barthelemy Y, Driss T. Assessment of isokinetic knee strength in elite young female basketball players: correlation with vertical jump. J Sports Med Phys Fit. 2015;55(12):1502–8.
28. Sapega AA, Nicholas JA, Sokolow D, Saraniti A. The nature of torque "overshoot" in Cybex isokinetic dynamometry. Med Sci Sports Exerc. 1982;14(5):368–75.
29. Sattler T, Sekulic D, Esco MR, Mahmutovic I, Hadzic V. Analysis of the association between isokinetic knee strength with offensive and defensive jumping capacity in high-level female volleyball athletes. J Sci Med Sport. 2015;18(5):613–8.
30. Sattler T, Sekulic D, Spasic M, Osmankac N, Vicente João P, Dervisevic E, Hadzic V. Isokinetic knee strength qualities as predictors of jumping performance in high-level volleyball athletes: multiple regression approach. J Sports Med Phys Fit. 2016;56(1–2):60–9.
31. Stock MS, Mota JA, Hernandez JM, Thompson BJ. Echo intensity and muscle thickness as predictors of athleticism and isometric strength in middle-school boys. Muscle Nerve. 2017;55(5):685–92.
32. Suchomel TJ, Sands WA, McNeal JR. Comparison of static, countermovement, and drop jumps of the upper and lower extremities in U.S. junior national team male gymnasts. Sci Gymnast J. 2016;8(1):15–30.
33. Thompson B, Ryan E, Sobolewski E, Smith D, Akehi K, Conchola E, Buckminster T. Relationships between rapid isometric torque characteristics and vertical jump performance in division I collegiate American football players: influence of body mass normalization. J Strength Cond Res. 2013;27(10):2737–42.

34. Tsiokanos A, Kellis E, Jamurtas A, Kellis S. The relationship between jumping performance and isokinetic strength of hip and knee extensors and ankle plantar flexors. Isokinet Exerc Sci. 2002;10(2):107–15.
35. Warburton DER, Jamnik VK, Bredin SSD, Gledhill N. The physical activity readiness questionnaire for everyone (PAR-Q+) and electronic physical activity readiness medical examination (ePARmed-X+). Health Fit J Can. 2011;4(1):3–23.
36. West D, Owen N, Jones M, Bracken R, Cook C, Cunningham D, Shearer D, Finn C, Newton R, Crewther B, Kilduff L. Relationships between force–time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players. J Strength Cond Res. 2011;25(11):3070–5.