BIOMECHANICAL FIELD TEST OBSERVATIONS OF GYMNASTS ENTERING PUBERTY

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This study examined growth, maturation and biomechanical jumping ability in 19 sub-junior gymnasts during one year of high performance training. Each sub-junior gymnast completed anthropometry, bone (pQCT), and biomechanical jumping tests, as well as Tanner surveys. Large increases in jumping power production were observed after one year of training. Leg stiffness doubled during the period of rapid height growth and then reduced closer to baseline levels six months later. Whereas ankle extensor stiffness increased more rapidly when height growth was slower, and leg stiffness was stabilising. This study demonstrated that high performance, sub-junior gymnastics training results in large improvements in jumping strength and power, but also identified potential signs of heighted injury risk.

KEY WORDS: growth, maturation, force, power, jump, injury.

INTRODUCTION: Hopping and jumping are fundamental movement actions that are acquired, adapted, and refined for specific skills in gymnastics from an early age. Muscle strength and the ability to develop force rapidly via short bursts of high intensity power production play a major role in hopping and jumping skills (Bencke et al., 2010). Field tests of these movement attributes in gymnastics has included squat, countermovement, long (horizontal), and rebound jumps; as well as continuous hopping and jumping tests (Bradshaw & Le Rossignol, 2004; Moresi et al., 2010). The squat jump, for example, provides a baseline measure of a gymnast's concentric explosive strength. Squat jump power has been identified as a key attribute for vaulting ability (Bradshaw & Le Rossignol, 2004; Koperski et al., 2010). Whereas, a countermovement jump provides a measure of a gymnast's ability to utilise active muscle and elastic energy (Komi, 2000), and a rebound jump indicates a gymnast's level of motor coordination and their ability to perform dynamic stretch shortening cycle action under increasing eccentric loads (Walshe & Wilson, 1997). Numerous cross-sectional studies have examined these jump tests using either contact mats (e.g. Marina et al., 2012) or force platforms (e.g. Bradshaw & Le Rossignol, 2004). Only one study to date has examined longitudinal changes to jump power in gymnasts (French et al., 2004), but was limited by missing body mass data and therefore raw power measures. The effects of chronological and developmental (maturation) age, as well as competition level has also not been examined in relation to jump power development. The purpose of this study was to examine the development of jump power in sub-junior gymnasts during one year of high performance training.

METHODS: Nineteen gymnasts aged 9-13 years (Age = 11.27 $\pm$ 0.90 years; Height = 1.38 $\pm$ 0.07 m; Mass = 31.44 $\pm$ 4.96 kg) who were injury free at the time of testing, participated in the study. All of the gymnasts were selected to participate in a sub-junior national development camp and compete at the international development levels 6 to 10. All of the gymnasts in this study attended three camps after a major National competition. Each camp was 6 months apart. All procedures were approved by the Australian Catholic University and the Australian Institute of Sport Ethics Committees, and athlete assent and parental/guardian consent was obtained prior to participation in the study.
Anthropometry, Maturation, and Bone Measures: Each gymnast's height, body mass, limb lengths (foot, humerus, radius, femur, tibia, tibia to floor), and segment widths (shoulder, hip) were measured. Participants completed Tanner staging via self-assessed pubertal rating for pubic hair and breast or genital development, and self-reported menstrual cycle, where appropriate. The nondominant tibia was measured by pQCT (XCT 2000; Stratec Medizintechnik, Pforzheim, Germany) using software version 5.50d. Scans were performed at 4 % (distal site), 14%, 38%, and 66 % (proximal site) of bone length (measured as a

relative distance from the distal end of the bone). Volumetric trabecular bone mineral density was measured at the 4 % distal site after the removal of cortical bone. A contour mode with a threshold of 180 mg/cm^3 was used to separate soft tissue and bone to analyze trabecular bone. A constant default threshold of 711 mg/cm^3 was used to identify and remove cortical bone. Estimates of bone strength index (strength strain index, SSI mm^3) were provided by the manufacturer's software. The precision of repeat measurements in our department is 0.8% to 2.9% at the tibia after repositioning in 8 adults. Repeat measurements were not undertaken with children because of the need to minimize cumulative radiation exposure.

Biomechanical Measures: All of the participants performed a self-administered warm-up prior to the testing. Each gymnast then completed three trials of a squat jump (SJ), countermovement jump (CMJ), as well as rebound jump (RJ) from 82 cm and 120 cm boxes. The gymnasts also completed 10 continous hops (CH), 10 continuous jumps (CJ10), and 30 s of continous jumping (CJ30). All hop and jump tasks were performed doubled legged, barefoot, and at a self-selected pace. To minimize the effect of fatigue all participants were given approximately 30 seconds recovery time between each jump, and 1-2 minutes between each jump type. During the SJ, a self-selected starting depth was held for 2 s prior to each jump. The participants were instructed to jump as high as possible in the SJ and CMJ trials, and jump as high as possible whilst minimizing ground contact time for the DJ, CH, CJ10, and CJ30 trials. All of the hop and jump tests, excluding the RJs, were completed on a uniaxial force platform (Quattro, Kistler, Winterhur, Switzerland, 500 Hz) covered with two 3 cm thick, high density carpeted foam mats. The average result was recorded for each gymnast from the Quattro jump software (version 1.0.9.2). The RJs were completed on two portable, triaxial force plates (9286A, Kistler, Winterhur, Switzerland, 1000Hz). Both force plates were also covered with high density foam mats (6 cm). Accounting for the force plate and foam mats the resulting drop depths were 72.5 and 110.5 cm respectively for the two boxes. The force-time data was exported from the Bioware software (version 5.0.3.0, Kistler, Winterhur, Switzerland) into a custom-written Microsoft excel spreadsheet for analysis (e.g. contact time, peak force) where the vertical forces were combined. RJ displacement was calculated using the impulse-momentum method (Linthorne, 2001). Peak force data for all hops and jumps were normalized to body weight (BW). Power and stiffness measures were normalised to body mass (kg) and contact time (s) respectively.

Statistics: All data was collated and analysed statistically using SPSS for Windows software (SPSS Inc., Illinois, version 21.0). An alpha level of 0.05 was set for all analyses. Data were tested for normal distribution prior to parametric statistics using a Shapiro-Wilk test. Means and standard deviations are reported for descriptive statistics. A repeated measures analysis of variance (RM ANOVA) with post-hoc pairwise comparisons was used to identify differences between testing occasions (0, 6 & 12 months).

RESULTS: The majority of the gymnasts were pre-adolescent at the start of the study (Tanner = 1.18 ± 0.40) and entering puberty towards the end (Tanner = 1.73 ± 0.79; $p=0.025$). The gymnasts grew rapidly during the summer/autumn (0 – 6 month) period of the study (Height = 137.65 ± 6.84 cm → 141.04 ± 7.04 cm; $p<0.001$), with decreased growth during the winter/spring (6 – 12 month) period (Height = 141.04 ± 7.04 cm → 142.86 ± 6.76 cm; $p<0.001$). Whereas the gymnasts body mass gain was relatively consistent at approximately 2 kg every 6 months (Mass = 31.44 ± 4.96 kg → 33.44 ± 5.34 kg → 35.10 ± 6.05 kg; $p<0.001$). On average the gymnasts grew 4% in height ($F = 1012.96$, $p<0.001$) and gained 12% in mass ($F = 51.70$, $p<0.001$) during the study. The greatest change in the gymnasts' anthropometry was observed for tibia length. Overall a 9% increase in tibia length was observed during the study ($F = 57.81$, $p<0.001$). The growth pattern for the tibia reflected that of the gymnasts height (Tibia Length = 30.86 ± 2.42 cm → 33.30 ± 2.34 cm → 33.71 ± 2.74 cm; $p<0.001$ [0-6 months & 0-12 months only]). The stress strain index of the tibia increased by 14% ($F = 16.28$, $p<0.001$) from 855.83 ± 201.71 mm^3 at the start of the study to 943.81 ± 225.57 mm^3 at 6 months ($p<0.001$), and 972.84 ± 232.44 mm^3 at 12 months (6-12 months, $p<0.006$; 0-12 months, $p<0.001$).

The results for the jump tests are presented in Tables 1-3. A 9% decrease in CMJ displacement was observed, however a 48% increase was observed in force production at the eccentric-concentric transition and a 14% increase in average take-off power (Table 1). The self-selected pace of all of the continuous jumping and hopping tasks significantly decreased during the 12 month period. The frequency of the CJ10 test decreased from 2.01 ± 0.44 Hz at 0 months to 1.96 ± 0.10 Hz at 12 months ($F = 4.84$, $p=0.029$, ↓2%), and the CH frequency decreased from 1.82 ± 0.08 Hz at 0 months to 1.72 ± 0.11 Hz at 12 months ($F = 6.09$, $p=0.012$, ↓6%). The CJ30 frequency also decreased from 1.65 ± 0.27 Hz at 0 months

Table 1: Squat and countermovement jump test results.

Test	SJ Crouch Depth (cm)		CMJ Eccentric-Concentric Transition Force (BW)		CMJ Peak Force (BW)		CMJ Average Power (W/kg)		CMJ Displacement (cm)	
	M	SD	M	SD	M	SD	M	SD	M	SD
N	12		17		17		17		17	
0 months	-11.33	3.32	1.56	0.70	3.00	0.60	25.11	3.54	35.37	4.31
6 months	-15.79	4.16	1.98	0.59	3.27	0.51	28.25	3.48	34.04	2.94
12 months	-15.73	4.92	2.31	0.61	3.52	0.67	28.70	4.06	32.24	3.77
Main Effect	F	p	F	p	F	p	F	p	F	p
	5.29	0.027	6.01	0.012	3.90	0.043	6.10	0.012	4.39	0.031
0 vs 6	0.006		ns		ns		0.003		ns	
0 vs 12	0.025		0.003		0.013		0.006		0.008	
6 vs 12	ns		0.038		ns		ns		ns	
Direction	↑ 39%		↑ 48%		↑ 18%		↑ 14%		↓ 9%	

Table 2: Continuous jumping (CJ10) and hopping (CH) results.

Test	CJ10 Crouch Depth (cm)		CJ10 Eccentric-Concentric Transition Force (BW)		CJ10 Stiffness (kN/m)		CJ10 Normalised Stiffness (kN/m/s)		CJ10 Displacement (cm)		CH Stiffness (kN/m)		CH Normalised Stiffness (kN/m/s)		CH Displacement (cm)	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
N	14		14		14		14		14		17		14		17	
0 months	-9.24	2.31	5.36	0.94	15.75	6.61	7.69	2.82	24.87	4.16	21.19	4.65	11.63	3.50	16.44	2.33
6 months	-5.10	1.95	5.25	0.96	34.23	21.73	15.39	9.38	29.39	3.69	21.20	4.39	11.28	2.89	18.89	2.62
12 months	-7.37	3.10	4.18	0.89	19.45	13.55	8.69	5.75	32.22	3.21	24.09	6.21	13.87	4.09	20.71	4.75
Main Effect	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p
	14.71	0.001	12.95	0.001	4.89	0.028	4.77	0.030	13.84	0.001	4.23	0.035	4.19	0.036	6.44	0.010
0 vs 6	<0.001		ns		0.007		0.007		<0.001		ns		ns		0.011	
0 vs 12	ns		0.001		ns		ns		<0.001		0.013		0.015		0.004	
6 vs 12	0.036		<0.001		0.020		0.018		0.011		0.013		0.016		ns	
Direction	↓ 20%		↓ 22%		↑ 23%		↑ 13%		↑ 30%		↑ 14%		↑ 19%		↑ 26%	

Table 3: Continuous jumping (CJ30) and rebound jumping (RJ) results.

Test	CJ30 Crouch Depth (cm)		CJ30 Eccentric-Concentric Transition Force (BW)		CJ30 Power (W/kg)		CJ30 Displacement (cm)		RJ73 Displacement (m)		RJ111 Peak Force (BW)		RJ111 Displacement (m)		RJ111 Peak Eccentric Power (W/kg)	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
N	16		16		16		16		9		9		9		9	
0 months	-7.92	2.82	5.45	0.70	31.21	4.72	25.04	3.29	13.50	2.65	12.24	1.85	13.24	2.06	-353.88	61.86
6 months	-4.58	1.65	5.40	0.92	34.63	6.09	30.31	3.75	16.07	3.61	12.28	1.64	16.49	3.40	-360.12	50.40
12 months	-5.54	3.01	4.74	0.98	34.04	6.15	31.34	3.41	17.89	3.90	13.05	1.72	16.69	3.98	-391.80	51.33
Main Effect	F	p	F	p	F	p	F	p	F	p	F	p	F	p	F	p
	10.67	0.002	6.02	0.013	4.55	0.030	54.64	<0.001	8.66	0.013	4.81	0.05	4.89	0.047	6.26	0.028
0 vs 6	0.001		ns		0.010		<0.001		ns		ns		0.016		ns	
0 vs 12	0.005		0.009		0.026		<0.001		0.002		0.012		0.023		0.006	
6 vs 12	ns		0.005		ns		ns		0.029		ns		ns		0.032	
Direction	↓ 30%		↓ 13%		↑ 9%		↑ 25%		↑ 33%		↑ 7%		↑ 26%		↑ 11%	

to 1.49 ± 0.12 Hz at 12 months (F = 4.59, p=0.029, ↓9%). Coinciding with the gymnasts rapid growth in height, the gymnasts normalised leg stiffness (CJ10; normalised to jump frequency) also rapidly increased by 100% from 7.69 ± 2.82 kN/m/s to 15.39 ± 9.38 kN/m/s,

and then dropped by 77% closer to baseline levels during the final 6 months 8.69 ± 5.75 kN/m/s (F = 4.77, p=0.030). Whereas the gymnasts normalised ankle extensor stiffness (CH) increased by 19% during the 12 months (F = 4.19, p=0.036), with the largest change observed during the slower, winter/spring growth period (CJ10 Normalised Stiffness = 11.28 ± 2.89 kN/m/s at 6 months, CJ10 Normalised Stiffness = 13.87 ± 4.09 kN/m/s at 12 months, p<0.016, 23%). The gymnasts showed a 9% increase in average take-off power during the longer CJ30 test (F = 4.55, p=0.030). For the rebound jumps, the greatest improvements were observed for the higher box, particularly for displacement (F = 4.89, p=0.047, ↑26%) and peak eccentric power (F = 6.26, p=0.028, ↑11%).

DISCUSSION AND CONCLUSION: Large increases in jumping power production were observed after one year of training. The gymnasts improved most in producing greater CMJ power and also peak eccentric power during the 111 cm RJ. This indicates that the gymnasts have developed greater strength potential for more advanced floor tumbling, vaulting, and beam acrobatic skills. Leg stiffness doubled during the period of rapid height growth and then reduced closer to baseline levels six months later, indicative of a potential window for heighted injury risk (e.g. lower back, knee) (Bradshaw & Hume, 2012). Whereas ankle extensor stiffness increased more rapidly when height growth was slower, and leg stiffness was stabilising which represents a possible second phase of injury risk (e.g. Achilles tendinopathy) (Bradshaw et al., 2006). As the gymnasts were not re-tested again 6-12 months later, it is unknown if the increased ankle extensor stiffness was permanent or variable. However this study does suggest that there is a link between growth and lower extremity stiffness that may lead to injury. Further analyses of this data set will examine the relationship between these measures with injury.

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