ASSOCIATION BETWEEN MUSCLES' CONTRACTILE PROPERTIES AND JUMPING PERFORMANCE IN GYMNASTS

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Original article

Abstract
This study examined the association between muscles' contractile properties and jumping skill performance in gymnasts. Thirty-nine internationally experienced female (56%) and male (44%) gymnasts participated in the study. Radial displacement and contraction time of the biceps femoris, rectus femoris, vastus lateralis, vastus medialis, and erector spinae were collected to assess muscles' contractile characteristics using tensiomyography (TMG). Additionally, peak power, jump height, vertical take-off velocity, and vertical peak force in squat jump, countermovement jump, and drop jump were recorded. The TMG parameters did not predict jumping performance in our sample of female and male gymnasts. Associations between TMG parameters and jumping performance are discussed in the article.

Keywords: *artistic gymnastics, countermovement jump, squat jump, drop jump, explosive power.*

INTRODUCTION

The purpose of a jump in artistic gymnastics is to perform turns, twists, and/or to reach a desired posture in the air. Exhibition of strength, power, flexibility, and spatial awareness is needed to perform jumps, leaps, hops, and acrobatic skills with control and amplitude, allowing errorless execution. Performance of ballistic movements, such as jumps, leaps, hops, or sprints is clearly determined by high levels of force, power, and velocity (Cormie, McGuigan, & Newton, 2011a, 2011b; Cronin & Sleivert, 2005). Explosive power is the main determinant of performance (i.e., height of a jump) in such activities because it determines velocity at release or take-off. The take-off velocity, however, is determined by the force the muscles generate against the floor and the time during which the forces are applied (Newton & Kraemer, 1994). Production of peak power or the highest power value achieved during a jump, peak velocity, peak force, and jump height are the most important variables to describe leg muscle explosive function for athletes (Riggs & Sheppard, 2009; Young, Cormack, & Crichton, 2011).

One of the conventional tests used to assess explosive power is the vertical jump. It is usually conducted in three variations: (a) squat jump (SJ), (b) countermovement jump (CMJ), and (c) drop jump (DJ). All of aforementioned jump tests are reliable and valid measures for the estimation of explosive power of the lower limbs (Arteaga, Dorado, Chavarren, & Calbet, 2000; Markovic, Dizdar, Jukic, & Cardinale, 2004; Viitasalo, 1988) and are used as 'gold standard' tests in scholarly literature. Additionally, the characteristics of the CMJ with arm swing were found to be similar to standing back somersaults performed on the spot (Mkaouer, Jemni, Amara, Chaabèn, & Tabka, 2012).

In order to enhance power production in jumping, certain properties of involved muscles are needed. For example, one of the factors that significantly influences power performance in jumping is muscle stiffness (Chelly & Denis, 2003; Watsford, Ditroilo, Fernández-Peña, D'Amen, & Lucertini, 2010). To maximize vertical take-off velocity and mean mechanical power, the proper muscle stiffness has to be employed (Arampatzis, Schade, Walsh, & Brüggemann, 2001). Tensiomyography (TMG) is one of the reliable and valid methods used to measure contractile properties of the muscle. It can be used as an injury diagnostic tool or as a tool for monitoring training effectiveness. Radial displacement (Dm) of a given muscle measured with TMG is thought to reflect the muscle contractile force and muscle stiffness (Dahmane, Djordjevič, Šimunič, & Valenčič, 2005; García-Manso et al., 2012, 2011; Križaj, Šimunič, & Žagar, 2008; Pišot et al., 2008). Additionally, TMG can also measure the duration of the muscle contraction (Tc) which can be associated with higher contraction velocities. It has been proven that shorter Tc correlates with running speed for 20m flying sprint (Dahmane, Djordjevič, & Smerdu, 2006). Consequently, it is plausible that Dm and Tc could be indirectly associated with performance in motor tasks involving a stretch-shortening cycle (i.e., jumping skills), during which power production is essential. Lower Dm which corresponds to a greater muscle stiffness and lower Tc which corresponds to higher contraction velocities could indicate superior jumping performance.

To our knowledge there has been only one study conducted that investigated the association between TMG parameters and performance in power-related motor tasks. Gil et al. (2015) conducted a study on 20 elite soccer players which investigated the association between TMG parameters (Dm and Tc) and jumping and sprinting abilities. They found the following significant associations between TMG parameters and parameters from countermovement jump, drop jump tests, and 25 m maximal-effort sprints: (a) a moderate negative association between Dm of the biceps femoris and contact time, (b) a moderate negative association between Dm of the rectus femoris and contact time, and (c) a moderate association between Dm of the biceps femoris and reactive strength index. The lack of associations was discussed as a deficiency of TMG in measuring coordinative and control parameters that are also involved in complex jumping tasks. In contrast to jumping and sprinting tasks, where several muscles are involved in movement, some muscles also transfer power between joints; the TMG measures a muscle in an isolated environment. Dm and Tc seem to imply higher muscle stiffness and could be considered a valid measure for stretch-shortening cycle efficiency, but in the aforementioned study they lack the ability to predict jumping performance due to the study's insensitivity to the task complexity.

Whether associations between TMG parameters and jumping performance would be different when (a) measuring athletes from other sports, (b) measuring TMG parameters on other muscles involved in jumping than the rectus and biceps femoris, and (c) using other variables for measuring jumping performance, are questions which remain unanswered. The purpose of the present study is to investigate the association between TMG parameters and jumping skill performance in gymnasts.

Stretch-shortening cycle efficiency is very important for performance in soccer and gymnastics, and enables athletes to jump high and in a required direction. However, jumping technique between soccer players and gymnasts differs significantly, because they train and compete in different environments. Soccer is played on a soccer pitch with little elasticity and gymnasts perform on the gymnastics floor, vault, balance beam, etc., which have good elasticity; this probably affects the jumping technique. It has been proven before that the elasticity of different training surfaces could lead to diverse muscle responses (Rojas-Barrionuevo, Vernetta-Santana, Alvariñas-Villaverde, & López-Bedoya, 2017), indicating different muscle adaptations to different training characteristics in the long term. Gymnasts' jumping is characterized by an extremely fast force development because of the time constraints of the tumbling take-offs that take less than 150 ms (Marina, Jemni, & Rodríguez, 2013; Marina, Jemni, Rodríguez, & Jimenez, 2012). A soccer game is played for 90 minutes during which time players run as far as 15 km. A gymnastics competition lasts for approximately 120 minutes with the longest routine for women/men lasting 90/70 seconds (limited by the Code of Points (Federation Internationale De Gymnastique, 2017a, 2017b)) in which gymnasts perform up to 20 jumping gymnastics skills. These skills are technically determined by gymnastics rules and are very demanding in their complexity. The execution of jumping skills is not predetermined in soccer, but they are demanding mostly due to the unpredictable environment that a soccer match creates. It might be that TMG parameters would be able to predict jumping performance in gymnasts who use different jumping techniques in comparison with soccer players. It is hypothesized that TMG parameters are positively associated with parameters indicating leg muscle explosive function during jumping skills.

METHODS

Thirty-nine gymnasts, who are all internationally experienced competitors, participated in the study. The sample comprised 22 (56%) female gymnasts aged 15.76 ± 3.39 years (height: 159.14 ± 5.21 cm; weight: 49.00 ± 5.94 kg) and 17 (44%) male gymnasts aged 17.40 ± 6.08 years (height: 158.35 ± 13.03 cm; weight: 53.29 ± 15.02 kg). The local ethics committee approved the procedure of the study. All participants were informed about the aim of the study and signed their informed consent prior to the study.

The testing procedure consisted of (a) a TMG measurement protocol and (b) jump tests. Participants performed familiarization sessions with all testing procedures one day before attending a testing session which was used for the analysis.

TMG measurement protocol: Radial displacement (Dm) and contraction time (Tc) of the biceps femoris (BF), rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), and erector spinae (ES) muscles were collected using a TMG device (TMG Measurement System, TMG-BMC Ltd., Ljubljana, Slovenia). The validity of the TMG parameters has been proven before (Ditroilo, Smith, Fairweather, & Hunter, 2013; Križaj et al., 2008; Martín-Rodríguez, Loturco, Hunter, Rodríguez-Ruiz, & Munguia-Izquierdo, 2017; Ruiz et al., 2012; Tous-Fajardo et al., 2010; Wilson, Johnson, & Francis, 2018; Žagar & Križaj, 2005). The electric pulse amplitude started at 30mA and was increased by 10mA until maximal Dm was reached. A 30 s resting period was allowed between electrical stimuli to avoid potentiation effects (Wilson et al., 2018). The same assessor, who was familiar with the protocol, conducted the measurements.

Jump tests: Three variations of the jump test were conducted: (a) squat jump (SJ), (b) countermovement jump (CMJ), (c) drop jump (DJ). Three jumps were performed for each test variation on a force platform (S2P d.o.o., Ljubljana, Slovenija) that measured three-dimensional kinetic data; participants' hands were on their hips. The trial which produced peak jump height was used for analysis. DJ was performed from a 35 cm height. Jump height (JH), peak power value (P_{peak}), vertical take-off velocity (Vy), and peak vertical force value (F_{peak}) were recorded and used for analyses. Peak power and peak force were normalized by dividing peak power and peak force value by the corresponding weight of the participant.

Statistical analyses were performed using SPSS 21 (SPSS Inc., Chicago, USA). The Shapiro–Wilk test showed that the data were normally distributed. The percentage coefficient of variation (CV) and intra-class correlation (ICC) were calculated to verify the reliability of Tc, Dm, and JH for individual jump variation. For this study, a CV <20% was considered a good reliability and an ICC of <0.50, between 0.50–0.75, between 0.75–0.90, and >0.90 were considered poor, moderate, good, and excellent, respectively.

Pearson correlation was used independently for women and men to check the level of association between TMG parameters and JH, P_{peak}, Vy, and F_{peak} for each jumping variation. Correlation coefficient values <0.10 were considered as trivial, 0.10–0.30 as small, 0.30–0.50 as medium, and >0.50 as large. Significance level was set at $p < .05$.

RESULTS

All statistical assumptions were met for the analyses. CV and ICC revealed good to excellent reliability for TMG (for Tc CV = 1.0%–13.0%, ICC = 0.78–0.83; for Dm CV = 1.0%–19.8%, ICC = 0.63–0.89), and jump tests (for CMJ CV = 1.0%–14.0%, ICC = 0.98; for SJ CV = 1.0%–15.0%, ICC = 0.90; for DJ CV = 2.0%–19.0%, ICC = 0.92).

Descriptive statistics from TMG assessments and jumping performance are shown in Table 1. Statistically significant differences were found between sex for JH and Vy in CMJ ($p < .05$), Dm in ES ($p < .05$), and Dm in VM ($p < .05$). Significant associations between TMG parameters and jumping performance for men are shown in Tables 2–4 and for women in Table 5.

Significant large and positive correlations were found between Dm of ES and jump height (r = .679, p = 0.003), peak power (r = .611, p = 0.009), and vertical take-off velocity (r = .681, p = 0.003) for CMJ (Table 2). Thus, higher jump, with higher power production and higher vertical take-off velocity are associated with higher Dm values which correspond to lower muscle stiffness.

Significant moderate and positive correlation was found between Tc of ES and peak power (r = .495, p = 0.043) for DJ (Table 3). Higher peak power is associated with longer Tc when performing DJ.

Significant large and negative correlation between Tc of BF and vertical take-off velocity (r = -.507, p = 0.038) was found in SJ, indicating that shorter Tc is associated with higher vertical take-off velocity. However, significant moderate and positive correlation between Tc of VL and vertical take-off velocity (r = .483, p = 0.049) was found (Table 4).

Significant large and positive correlations between Dm of ES and jump height (r = .579, p = 0.015), peak power (r = .618, p = 0.008), and vertical take-off velocity (r = .588, p = 0.013) were found, indicating that superior jumping performance is associated with higher Dm values which correspond to lower muscle stiffness. Additionally, significant large and positive correlation between Dm of VL and vertical take-off velocity (r = .539, p = 0.026) was found, indicating that higher vertical take-off velocity is associated with higher Dm values which correspond to lower muscle stiffness.

Significant moderate and negative correlation between Dm of VL and jump height (r = -.457, p = 0.032) in DJ was found for women (Table 5). Thus, higher jumps are associated with lower Dm which corresponds to higher muscle stiffness. No significant correlations were found

between TMG, CMJ, and SJ (all $p > 0.05$)
for women, respectively.

Table 1
Performance characteristics' Mean ± SD during the CMJ, DJ, SJ, and TMG measurements.

Measure	Variable	Male (n = 17)		Female (n = 22)	
CMJ	JH (m)	0.32	± 0.05*	0.28	± 0.04
	P_{peak} (W/kg)	47.09	± 4.39	44.28	± 4.69
	Vy (m/s)	2.50	± 0.17*	2.39	± 0.13
	F_{peak} (N/kg)	24.95	± 2.36	25.26	± 3.04
DJ	JH (m)	0.26	± 0.04	0.27	± 0.05
	P_{peak} (W/kg)	70.01	± 14.43	72.05	± 9.23
	Vy (m/s)	2.28	± 0.20	2.30	± 0.13
	F_{peak} (N/kg)	56.45	± 11.34	56.96	± 7.98
SJ	JH (m)	0.31	± 0.06	0.29	± 0.06
	J P_{peak} (W/kg)	48.22	± 6.39	47.45	± 6.18
	Vy (m/s)	2.39	± 0.20	2.30	± 0.15
	F_{peak} (N/kg)	23.54	± 2.40	24.06	± 2.36
TMG	Tc BF (ms)	21.50	± 3.86	24.30	± 6.36
	Tc ES (ms)	14.76	± 1.37	14.57	± 1.53
	Tc RF (ms)	19.89	± 2.97	20.53	± 2.80
	Tc VL (ms)	17.27	± 1.65	16.69	± 1.33
	Tc VM (ms)	18.89	± 1.76	18.21	± 1.40
	Dm BF (mm)	4.11	± 1.75	4.03	± 2.05
	Dm ES (mm)	5.20	± 1.60*	4.19	± 1.25
	Dm RF (mm)	5.96	± 2.11	5.42	± 1.50
	Dm VL (mm)	4.66	± 1.47	4.10	± 1.13
	Dm VM (mm)	6.24	± 1.33*	4.95	± 1.18

Note. CMJ – counter movement jump; DJ – drop jump; SJ – squat jump, TMG – tensiomyography; JH – jump height; P_{peak} –peak power; Vy – vertical take-off velocity; F_{peak} –peak force; *p <.05; Tc – contraction time; Dm – maximal radial displacement; BF – biceps femoris; ES – erector spinae; RF – rectus femoris; VL – vastus lateralis; VM – vastus medialis.

Table 2
Pearson correlations between TMG and CMJ for men.

		JH (m)		P_{peak} (W/kg)		Vy (m/s)		F_{peak} (N/kg)	
		r	p	r	p	r	p	r	p
Tc	BF	-.321	.210	-.225	.386	-.219	.397	-.039	.880
	ES	.196	.450	.395	.117	.290	.258	.255	.323
	RF	-.158	.545	-.195	.454	-.206	.429	.008	.977
	VL	.250	.333	.250	.333	.278	.280	.329	.197
	VM	.357	.159	.295	.251	.310	.226	.210	.418
Dm	BF	-.427	.087	-.095	.718	-.398	.113	.036	.891
	ES	.679	.003*	.611	.009*	.681	.003*	.051	.845
	RF	.079	.762	.131	.617	.044	.865	.092	.725
	VL	.267	.301	.432	.083	.291	.258	.283	.271
	VM	.069	.792	.168	.519	.066	.801	.273	.290

Note. JH – jump height; P_{peak} –peak power; Vy – vertical take-off velocity; F_{peak} –peak force; r – Pearson's correlation coefficient; *p <.05; Tc – contraction time; Dm – maximal radial displacement; BF – biceps femoris; ES – erector spinae; RF – rectus femoris; VL – vastus lateralis; VM – vastus medialis.

Table 3
Pearson correlations between TMG and DJ for men.

		JH (m)		P_{peak} (W/kg)		Vy (m/s)		F_{peak} (N/kg)	
		r	p	r	p	r	p	r	p
Tc	BF	-.478	.052	-.104	.690	-.424	.090	.138	.596
	ES	.244	.346	.495	.043*	.120	.645	.388	.124
	RF	.014	.957	.145	.579	-.282	.274	-.070	.789
	VL	.258	.318	.251	.330	.181	.488	.239	.355
	VM	.354	.163	.148	.571	.440	.077	-.165	.528
Dm	BF	-.161	.536	-.024	.928	-.119	.650	.166	.525
	ES	.205	.430	.320	.211	.368	.147	.298	.245
	RF	.282	.273	.292	.255	.032	.904	.115	.661
	VL	.254	.325	.273	.290	.236	.361	.329	.198
	VM	.133	.610	.096	.714	.313	.221	.142	.587

Note. JH – jump height; P_{peak} –peak power; Vy – vertical take-off velocity; F_{peak} –peak force; r – Pearson's correlation coefficient; *p <.05; Tc – contraction time; Dm – maximal radial displacement; BF – biceps femoris; ES – erector spinae; RF – rectus femoris; VL – vastus lateralis; VM – vastus medialis.

Table 4
Pearson correlations between TMG and SJ for men.

		JH (m)		P_{peak} (W/kg)		Vy (m/s)		F_{peak} (N/kg)	
		r	p	r	p	r	p	r	p
Tc	BF	-.357	.160	-.300	.241	-.507	.038*	-.025	.924
	ES	.044	.867	.105	.687	.171	.511	-.068	.797
	RF	-.332	.192	-.241	.351	-.160	.540	.000	.999
	VL	.449	.070	.385	.127	.483	.049*	.136	.603
	VM	.210	.419	.091	.728	.220	.397	-.241	.351
Dm	BF	-.151	.564	-.074	.776	-.393	.118	.151	.563
	ES	.579	.015*	.618	.008*	.588	.013*	.231	.373
	RF	.062	.813	.211	.416	.188	.471	.373	.140
	VL	.460	.063	.520	.032	.539	.026*	.286	.266
	VM	.459	.064	.417	.096	.163	.532	.322	.208

Note. JH – jump height; P_{peak} –peak power; Vy – vertical take-off velocity; F_{peak} –peak force; r – Pearson's correlation coefficient; *p <.05; Tc – contraction time; Dm – maximal radial displacement; BF – biceps femoris; ES – erector spinae; RF – rectus femoris; VL – vastus lateralis; VM – vastus medialis.

Table 5
Pearson correlations between TMG and DJ for women.

		JH (m)		P_{peak} (W/kg)		Vy (m/s)		F_{peak} (N/kg)	
		r	p	r	p	r	p	r	p
Tc	BF	.031	.890	.207	.354	-.064	.776	-.006	.978
	ES	.063	.781	.037	.870	-.031	.891	-.072	.750
	RF	.164	.465	.043	.848	-.040	.860	-.197	.380
	VL	-.161	.474	.108	.632	-.256	.250	.184	.411
	VM	.269	.226	.061	.789	.316	.152	-.215	.336
Dm	BF	.031	.891	.026	.909	.116	.609	-.059	.793
	ES	-.093	.680	-.152	.499	-.020	.930	-.201	.371
	RF	-.145	.521	-.167	.458	-.230	.303	-.052	.818
	VL	-.457	.032*	-.111	.624	-.390	.073	.372	.071
	VM	.037	.871	-.060	.792	.130	.563	.007	.974

Note. JH – jump height; P_{peak} –peak power; Vy – vertical take-off velocity; F_{peak} –peak force; r – Pearson's correlation coefficient; *p <.05; Tc – contraction time; Dm – maximal radial displacement; BF – biceps femoris; ES – erector spinae; RF – rectus femoris; VL – vastus lateralis; VM – vastus medialis.

DISCUSSION

The results of the present study show: (a) large and positive correlations between Dm of the ES and jumping performance in CMJ and SJ for men; (b) moderate and positive correlation between Tc of ES and peak power in DJ for men; (c) large and negative correlation between Tc of BF and vertical take-off velocity in SJ for men; (d) moderate and positive correlation between Tc of VL and vertical take-off velocity in

SJ for men; (e) large and positive correlation between Dm of VL and vertical take-off velocity in SJ for men; and (f) moderate and negative correlation between Dm of the VL and jump height in DJ for women.

We believe the cause for higher muscle stiffness of the ES associated with inferior jumping performance lies in possible lower back problems. All potential participants with lower back injuries were excluded from the study; however, there were some participants who reported minor lower back problems. A stiff ES could indicate lower back problems where motion of the injured structures is prevented after acute trauma or as a hyperactive response of the muscle to pain (pain–spasm–pain model) (Van Dieën, Selen, & Cholewicki, 2003). It is plausible that participants without lower back problems produced more power and velocity during the support phase of CMJ and SJ, and thus reached higher jump height in contrast to participants with lower back problems. The activation of ES is supposed to enhance vertebral stability, allowing effective arm and leg movements as well as effective trunk extension (Shinkle, Nesser, Demchak, & McMannus, 2012) and increased jumping performance. Therefore, healthy trunk extensors are important for jumping performance. However, because we did not diagnose lower back muscle problems with other diagnostic tools in our study, it was impossible to demonstrate direct associations between lower back problems and jumping performance. According to point (b) of our results, it could be claimed that force produced in ES is more important than contraction time for power production in DJ. This could indicate that it is more important to pre-activate the back muscles for DJ rather than activate them fast at floor contact. However, contraction time for the same muscle lacked significance for vertical take-off velocity and jump height. Therefore, it is impossible to associate lower contraction time of ES with superior DJ performance. One of the challenges in jumping is to find a compromise between keeping the shortening velocities (contraction times) of the muscles low, because this might decrease the force and consequently decrease the work, and maximizing them to optimize the vertical velocity of the centre of mass (Bobbert & Van Soest, 2001).

Antagonistic muscle co-contraction is known to increase the equivalent stiffness of a joint, thus stabilizing the joint and giving support to the agonistic muscles. In SJ, BF works as an antagonistic muscle whereas VL is one of four heads of the quadriceps muscle that works as an agonistic muscle. The hamstring muscles have to contract fast in order to give full support to the knee extenders; therefore, it is plausible that the shorter contraction time of BF is important for the vertical take-off velocity in SJ. Muscle action in vertical jump is to some extent mechanically linked. It has been found that changing activation timing of certain muscles (i.e., hamstrings) by as little as 2–3 milliseconds results in a marked (over 10%) difference in jump height (Prokopow, Szyniszewski, & Himeno, 2005). The control of m. vasti, m. soleus, hamstrings, and plantar flexors were found to be especially important for coordination in jumping. The strength of the vastus medialis and rectus femoris (Bradley, Olsen, & Portas, 2007; De Ruiter, Vermeulen, Toussaint, & De Haan, 2007; Earp et al., 2010) as well as activation of ES (Charoenpanich, Boonsinsukh, Sirisup, & Saengsirisuwan, 2013) during SJ has been suggested as a predictor of jump height.

It was hypothesized that higher muscle stiffness in knee extenders (e.g., VL) would predict superior jumping performance; however, our study failed to prove this. On the contrary, our results indicate that higher muscle stiffness is associated with inferior jumping performance. In SJ, the jump test which excludes arm contribution and active pre-stretching in the explosive power outcome of the jump, higher muscle stiffness did not enhance jumping performance.

A number of limitations of the present study have to be considered. First, the act of vertical jumping requires whole body participation and complex recruitment of the leg, trunk, and arm muscles. Hence, muscle stiffness and contraction time are only two of the factors influencing jump performance and could be compensated for by other factors involved. Second, not all muscles of interest are measurable using the TMG method because TMG can measure only superficial muscles. Third, current findings can only be applied to gymnasts. Fourth, there are still questions to be answered about the external validity of the TMG technique for applications in sports performance (Macgregor, Hunter, Orizio, Fairweather, & Ditroilo, 2018); direct links between TMG and muscle function are not known at present.

CONCLUSION

In the present study, the TMG parameters failed to predict jumping performance in our sample of female and male gymnasts. However, results indicate that healthy back muscles are very important for the explosive function of the leg muscle and, therefore, performance of jumping skills. The lower maximal radial displacement of the ES muscle could indicate back problems and be indicative of inferior jumping performance in gymnasts.

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