

Comparison of tensiomyographic neuromuscular characteristics skeletal muscle properties in gymnasts

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Abstract

Objective: The purpose of this study is a comparison of skeletal muscle characteristics in Slovenian gymnasts assessed by TMG and values of contraction properties of muscles, lateral symmetries, and the effect of aging on selected contraction properties of skeletal muscles in men's artistic gymnastics (MAG); women's artistic gymnastics (WAG) and rhythmic gymnastics (RG). This study is the first larger study to use the TMG method and in which top athletes from artistic and rhythmic gymnastics participated. **Materials and Methods:** A survey of 81 athletes from different disciplines was conducted as follows: MAG ($n = 26$), WAG ($n = 28$), and RG ($n = 27$). The athletes' average age was 15.41 ± 5.03 years. In this study, the contraction times of ten skeletal muscles for Slovenian gymnasts on the right and left sides of the body were compared: M. Biceps brachii, M. Triceps brachii, M. Biceps femoris, M. Erector spinae, M. Gastrocnemius lateralis, M. Gastrocnemius medialis, M. Rectus femoris, M. Tibialis anterior, M. Vastus lateralis, M. Vastus medialis. **Results:** In MAG, a statistically significant correlation between age and contraction time was found for m. VL and m. VM. In WAG, was found for m. GM. In RG was found for m. TA and m. VL for all at $p < 0.01$. **Conclusions:** A comparison between the left and the right side body shows a slight asymmetry. With TMG, we can assess the discipline's demands and help improve gymnasts' performances along with the safety of training. Tensiomyography has a high predictive ability to discriminate between the left and right sides of the body functionally.

Key Words: - tensiomyography, gymnastics, contraction time, asymmetry.

Introduction

Scientific results in sports have led to changes in both the concept of the athlete's preparation and sports theory. Selection and orientation to systematic training started almost 20 years ago in almost every sport (Bompa, 2001). This is why experts created diagnostic models for use in selection, and diagnostic models for monitoring changes i.e. the body's response to physical activity among young, middle-aged and elderly athletes.

Many studies can be found about young athletes' guidance in different sports, the effect of exercise on body composition, as well as the development of functional and loco-motor skills and qualities. In contrast, not a lot of information is available about the type and composition of skeletal muscle, especially in adolescents (Šimunič et al., 2011). This longitudinal study focuses on changes in skeletal muscle fibres in children in development (Glenmark et al., 1992). As the study describes, due to the invasiveness of the muscle biopsy method and correlated ethical questions, research of skeletal muscles is rarely done in sports - in gymnastics practically never. With development of the tensiomyography (TMG), which is scientifically proven, objective and reliable (Ditroilo et al., 2013; Jiménez et al., 2013; Šimunič, 2003;2012; Tous-Fajardo et al., 2010), more knowledge about the structure and properties of the muscles has been gained (Šimunič et al., 2005; Valenčič & Knez, 1997; Valenčič, 1990).

The TMG monitors radial muscle belly displacement under isometric conditions. A twitch type of electrical stimulus induces the concentric contraction of the muscle. Due to the maintenance of the muscle volume, the muscle thickens, causing the sensor to move and send the signal. The basic parameters of TMG are: Tc – contraction time, Dm – maximal displacement, Ts – sustain time, Td – delay time, Tr – relaxation time. Contraction time (Tc) and maximal displacement (Dm) are the most researched parameters of the TMG method in different sports. (Šimunič et al., 2005; Zurc, 2006). TMG is both a non-invasive as well as time and financially non-demanding method which can be used to define the structure of skeletal muscle and, on the basis of time parameters, data about the muscle function. The latter can be used for different analysis such as measurement of adaptation abilities of muscles to specific training or exercise, diagnosis of lateral and functional symmetries, measurement of muscle fatigue and control of a rehabilitation programme (Šimunič et al., 2011;

Šimunić, 2012). Studies have shown that muscle asymmetries increase the risk of injuries in different locations (Baumhauer et al., 1995; Bračič, 2010; Bračič et al., 2008; Coombs & Garbutt, 2002; Richards et al., 2002). Sensitive and accurate measuring devices for discovering muscle asymmetries are an isokinetic device, force plate and TMG (Samardžija & Zupet, 2014) except for the trunk where the TMG method is used to discover muscle asymmetries in modern sports diagnostics (Zurc, 2006). Asymmetries of the back muscles (m. Erector spinae) can lead to different back deformations and injuries (Avikainen et al., 1999; Jaremko et al., 2002). In addition to the basic parameters, it is useful to longitudinally monitor and study the correlation of different parameters over longer periods. In prior studies, the impact of age on contraction time was found (Dahmane, 2006; Šimunić et al., 2014). Competitive artistic gymnasts experience significant limb loading asymmetries when performing foundation floor skills. This is important knowledge for coaches and sports practitioners, considering the potential association between asymmetrical loading and injury. It also emphasizes that gymnasts have individualized responses, indicating that screening at the individual level is needed to accurately identify gymnasts and limbs that are at a higher risk for injury. Every gymnastics skill showed significant inter-limb asymmetry and every gymnast demonstrated intra-limb variability for at least one gymnastics skill (Campbell et al., 2021). A compilation of twenty gymnastics injury rate studies shows a large range of rates being 5.3 to 200 injuries per 100 gymnasts and 0.44 to 22.7 injuries per 1000 hours of participation (Dowdell, 2011), which makes elite gymnasts and younger gymnasts a risk population. Within artistic gymnastics, the floor apparatus is associated with the highest injury risk (Kirialanis et al., 2002). It is worth to note also asymmetric landing on hands i.e. exercise on one hand (e.g. round off and pommel horse elements) could have impact on injury rates of arms. From familiar gymnastics practice and from publicly known data, it can be assumed that most injuries are asymmetric (i.e. on one body side only).

Long-term asymmetric landing can probably cause acute injuries (mostly like in ankles or knees) or chronic injuries (most likely in the back trunk) (Yeadon, 1993; 1999). It is especially important that young gymnasts learn to perform every landing as symmetrically as possible (Čuk & Marinšek, 2013). Most sports have a degree of asymmetry. For instance, throwers in sports like baseball, basketball, football, handball and cricket have a dominant arm. This arm will undergo repetition and a higher volume of training. In contrast, a sport like gymnastics or swimming requires a much greater degree of symmetry. Gymnastics requires the use of both sides of body at different times and interval jumps, landing, takeoff, etc. Therefore, asymmetry would impair gymnasts' capacity for optimum performance and this is not ideal.

Review of Code Of Points (COP) revealed that it mostly contains elements (in 60% of cases) where a single leg at take-off or at landing is loaded (FIG, 2020^a, 2020^b). Researchers conclude that asymmetric lower limb loading is present at balance beam routines in elite gymnasts. They hypothesize that the unilateral distribution of load may be associated with the unilateral predominance of injuries (Čuk & Marinšek, 2013; Čuk, 2016). Throughout history, artistic gymnastics competitions have included both compulsory and optional exercises. Some situations required movement in both directions and on both sides. Today, COP in MAG and WAG have no words on symmetries, but MAG COP in article 1 paragraph 4 say: *the primary purpose of the COP is to guide coaches and gymnasts in the composition of competition exercises; also same text we can find in WAG COP*. Without a definition of symmetry in COP MAG and WAG, there is an impact on the creation of the exercise in the area of symmetry in the ordering element group and within difficulty, where it is crucial to increase the exercise's difficulty value. Hypothetical most difficulty exercises on each apparatus revealed that in general for all around gymnast proportion between asymmetric and symmetric elements is close to 70% to 30%, what suggests that difficulty relates to increased asymmetry. However, coaches' duties are to be mindful of COP influence on gymnasts' health, limit asymmetries in load, and focus on symmetric conditioning. COP in MAG and WAG pushes asymmetric motions for high performance (Čuk, 2016).

The purpose of this study was a comparison of skeletal muscle characteristics in Slovenian gymnasts assessed by tensiomyography and values of muscles' contractile properties, lateral symmetries, and the effect of aging on selected skeletal muscles' contractile properties in men's artistic gymnastics (MAG); women's artistic gymnastics (WAG) and rhythmic gymnastics (RG).

Material & methods

Samples

Measurements of ($n = 81$) athletes from different disciplines were conducted in this study: men's artistic gymnastics ($n = 26$ athletes), women's artistic gymnastics ($n = 28$ athletes) and rhythmic gymnastics ($n = 27$ athletes). Their average age was 15.41 ± 5.03 years. The study was approved 29.12.2020. year by Ethics Commission of the Gymnastics Federation of Slovenia of the Republic of Slovenia for Medical Ethics, approval study number: 485/2020 in line with the criteria of the Helsinki Declaration for research involving human beings. Commission agrees that the data for can be used for scientific purposes through the research project "*Development of an expert model of preparation and performance of athletes*". Average age of the gymnasts included in the study MAG 11-14 y. 11(42.3%), 15-18 y. 5(61.5%), 19-22 y. 3(73.1%), 23-26 y. 3(84.6%), 27-40 y. 4(100%); WAG 11-14 y. 21(75%), 15-18 y. 2(82.1%), 19-22 y. 3(96.4%), 23-26 y. 1(100%); RG 11-14 y. 19(70.4%), 15-18 y. 8(100%).

Table 1. Descriptive statistical data and differences between variables (according to disciplines).

Variable	Age (years)	BH (cm)	BW (kg)	BSA (m ²)
Disciplines	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
MAG n = 26 (32.1%)	18.46 (7.18)	160.51 (15.20)	56.85 (16.32)	1.58 (.30)
WAG n = 28 (34.6%)	14.32 (3.33)	155.05 (6.25)	45.78 (7.42)	1.40 (.13)
RG n = 27 (33.3 %)	13.59 (1.89)	156.84 (9.63)	42.87 (8.96)	1.36 (.18)

Abbreviations: BH, Body Height, BW, Body Weight, BSA, Body surface area.

Measured Muscles

The measurements lasted 30–35 minutes per athlete. We conducted one measurement of the left-side muscles and one measurement of the right-side muscles on a therapeutic desk, which provided comfort and exactly accommodated the athlete in a lying or sitting position. All muscles were relaxed before and after the measurement. The measurements were always taken between 9-12 am in a temperature-controlled room. During the measurements, the temperature was between 21 and 25 °C. Measurement of m. biceps brachii (m. BB) and m. triceps brachii (m. TB) was carried out in a sitting position. The measured upper extremity was 30° abducted in the shoulder, 90° flexed in the elbow (where 0° means a fully extended elbow), the forearm was pronated. To maintain this position, we used foam pads placed under the elbow (Dahmane, 2006). Measurement of m. rectus femoris (m. RF), tibialis anterior (m. TA), m. vastus lateralis (m. VL), m. vastus medialis (m. VM) were done in a lying position, where flexion of the knee was 30° (where 0° means a fully extended knee). To maintain this position, we used foam pads placed under the knee. The measurement of m. biceps femoris (m. BF), m. erector spinae (m. ES), m. gastrocnemius lateralis (m. GL) and m. gastrocnemius medialis (m. GM) were performed lying on the abdomen, with 5° of knee flexion (where 0° means a fully extended knee). To maintain this position, we used foam pads placed under the ankle (Šimunič et al., 2014).

Electrical Stimulation

Two surface electrodes were placed on the muscle belly in an appropriate position. After marking the sensor location, positioned the electrodes at ±7 cm. The electrodes were connected to an electric stimulator, which releases an electric stimulus lasting 1 millisecond with a power supply voltage of 12 V and output intensity from 0 to 110 Ma (Šimunič, 2003). For all athletes, we gradually increased the output intensity from 5 to 10 mA until the contraction time parameter reached the highest values or until the muscle response no longer increased (Dahmane et al., 2001). A sensor was placed on the muscle belly perpendicularly. The electric stimulus induced the muscle contraction, the muscle belly thickened and pushed the perpendicularly placed sensor away. The sensor measured the maximal displacement, contraction time, sustain time, delay time, relaxation time and sent the measurements for further computer analysis (Golob, 2008; Žiberna, 2003).

As suggested by (Valenčič & Knez, 2007) for each muscle response Dm, Td and Tr were calculated. Dm means maximal displacement of the muscle, Tc is defined as the time between 10% and 90% of the maximal displacement (Šimunič et al., 2014). Athletes were familiar with both the basic principles of the TMG method and the purpose of the measurements. They were also informed not to warm up or perform any strenuous activities before the measurements. The measurement protocol for each muscle was carried out once. The measurements were performed in a gymnastics centre in Slovenia in the first half of the day and lasted for 14 days.

Statistical Analysis

Data processing was done with IBM® SPSS® Statistics 27 and Microsoft Office 2013 – Excel. SPSS 27.0 was used for statistical analysis. Data is displayed as (mean, standard deviation) which included descriptive statistics, correlational analyses, *t*-tests. In order to check for any deviation from normality, a number of methods can be used. One method is to use skewness and kurtosis. Normality can be a problem when the sample size is small (<50). As can be seen in (Tables 2), for the purposes of conducting a *t*-test (i.e., Skewness < |3.0| and Kurtosis < |9.0|). In the present study, we explored many different formulas can be used to calculate body surface area. Our BSA calculator uses the most common form, the Mosteller formula (Table 1), by default. The main problem with BMI is that it doesn't distinguish between fat mass and non-fat mass.

Mosteller formula: $BSA = 0.016667 \times W^{0.5} \times H^{0.5}$

(1) Differences in the activity of each pair of muscles for each gymnast were confirmed by measuring the *t* test. Paired *t*-test was performed to determine whether there were any significant differences left and right side of body. Cohen's *d* is an effect size *r* used to indicate the standardised difference between two means. Some general rules of thumb are that |*d*| = 0.20 indicates a small effect; |*d*| = 0.50 indicates a medium effect; |*d*| = 0.80 indicates a large effect. Statistical analysis was performed with descriptive statistics (contraction time, laterality) and Pearson's correlation coefficient (the effect of age on the muscle contractility). 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. The significant level was defined as (*p* < 0.05). Symmetrical and synchronized muscle function is essential prerequisite for optimal performance in gymnastics. The newly developed TMG report is able to provide an immediate reflection of the results obtained during the test. This colour-coordinated report designates optimal, average, and poor muscle responses and muscle symmetries. This report designates: optimal 90-100%, average 80-89% (monitor), and poor <80% (concern) muscle responses and muscle symmetries.

Results

Skeletal muscles have different contraction times. Table 2 shows the lowest value was reached in m. ES (14.00 ± 1.3) in all three events and the highest value was reached in m. BF_R (RG 27.28 ± 6.46), BF_L (WAG 25.40 ± 4.94) and m. BB_R (MAG 24.46 ± 2.93). A peer-to-peer comparison of all three disciplines shows the smallest differences occur in the contraction time of m. MAG m. Biceps femoris, Rectus femoris and RG m. Vastus lateralis. Lateral symmetry i.e. a comparison of the left and right side is very useful, especially when preparing prevention programmes. In the analysis of all gymnastics disciplines it was found that the middle deviations are higher in WAG m. GL (10%). In WAG, the middle deviations are within limits, indicating a slight risk of pain or injuries. In MAG and RG, there is a no bigger deviation, which increases the risk of injuries or pain. Percentage differences are presented in (Table 2) m. Biceps brachii MAG 4%, m. Triceps brachii MAG 4%, m. Gastrocnemius lateralis WAG 10%, m. Tibialis anterior MAG 4%, m. Vastus lateralis MAG 4%, m. Vastus medialis WAG 4% and WAG 9%.

Table 2. Descriptive statistical data of the contraction time (Tc) parameter of selected skeletal muscles and deviations from lateral symmetry by disciplines MAG, WAG and RG.

Muscles	Disciplines	N	Right side (R)	Left side (L)	Diff.	Diff. %
			Mean (SD)		R-L	R-L
M. Biceps brachii	MAG	13	24.46 (2.93)	23.59 (3.41)	0.87	4%
	WAG	8	21.39 (2.06)	21.52 (3.01)	-0.13	-1%
M. Triceps brachii	MAG	13	18.12 (2.31)	17.34 (1.20)	0.78	4%
	WAG	8	16.34 (2.41)	15.99 (2.05)	0.35	2%
M. Biceps femoris	MAG	26	23.65 (3.69)	23.59 (5.36)	0.06	0%
	WAG	28	24.52 (4.19)	25.40 (4.94)	-0.88	-3%
	RG	27	27.28 (6.46)	26.56 (6.29)	0.72	3%
M. Erector spinae	MAG	26	14.94 (1.81)	14.68 (1.52)	0.26	2%
	WAG	28	14.64 (1.40)	14.48 (1.40)	0.16	1%
	RG	27	14.12 (1.32)	14.01 (1.36)	0.11	1%
M. Gastrocnemius lateralis	MAG	8	20.37 (2.46)	19.72 (1.69)	0.65	3%
	WAG	11	19.56 (2.22)	21.72 (3.47)	-2.16	-10%
	RG	18	19.40 (2.74)	19.91 (2.68)	-0.51	-3%
M. Gastrocnemius medialis	MAG	8	19.72 (1.58)	20.14 (2.14)	-0.42	-2%
	WAG	11	21.20 (4.62)	21.06 (3.57)	0.14	1%
	RG	18	20.49 (2.40)	20.17 (2.32)	0.32	2%
M. Rectus femoris	MAG	26	21.12 (2.99)	21.21 (3.56)	-0.09	0%
	WAG	28	21.00 (3.05)	21.66 (3.15)	-0.66	-3%
	RG	27	21.84 (2.56)	22.02 (2.48)	-0.18	-1%
M. Tibialis anterior	MAG	9	15.21 (1.15)	15.90 (2.00)	-0.69	-4%
	WAG	11	16.02 (1.03)	15.74 (1.20)	0.28	2%
	RG	18	16.25 (2.02)	15.81 (1.57)	0.44	3%
M. Vastus lateralis	MAG	26	17.70 (2.41)	18.50 (2.25)	-0.80	-4%
	WAG	27	17.38 (1.85)	17.57 (1.56)	-0.19	-1%
	RG	27	17.88 (1.76)	17.81 (2.32)	0.07	0%
M. Vastus medialis	MAG	26	19.77 (2.49)	19.94 (3.00)	-0.17	-1%
	WAG	28	19.37 (2.20)	18.55 (2.02)	0.82	4%
	RG	27	19.35 (2.27)	17.83 (1.90)	1.52	9%

Abbreviations: *Tc (ms) – contraction time in milliseconds (ms).

Concerning the correlation of contraction time with ageing, it was found that age can extend the contraction time in some muscles (Table 3). Despite the statistical significance, many correlations (r) are weak. A statistically significant correlation $0.40 \leq r \leq 0.70$ (Petz, 2007) was found in m. BB and m. VM. In MAG, a statistically significant correlation between age and contraction time was found for m. VL ($r = 0.432$, $p < 0.001$) and m. VM ($r = 0.482$, $p < 0.000$) at $p < 0.01$. In WAG, a statistically significant correlation between age and contraction time was found for m. GM ($r = 0.544$, $p < 0.009$) at $p < 0.01$. In RG, a statistically significant correlation between age and contraction time was found for m. TA ($r = 0.380$, $p < 0.022$) and m. VL ($r = 0.377$, $p < 0.005$) at $p < 0.01$. There is no relationship (r^2) between gymnastics disciplines MAG, WAG and RG the all variables together (Fig. 1).

Table 3. Pearson correlation coefficient (r) age (years) and contraction time (Tc) parameter of selected skeletal muscles by disciplines MAG, WAG and RG.

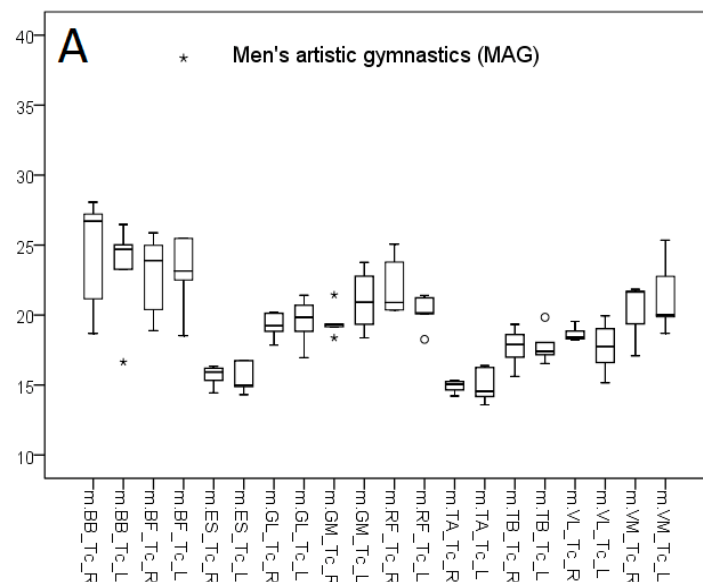
Disciplines		Age	BB	BF	ES	GL	GM	RF	TA	TB	VL	VM
MAG	r	1	.09	-.00	.19	-.42	.18	.19	-.11	.24	.43**	.48**
	p		.75	.96	.16	.10	.48	.16	.66	.23	.00	.00
	N	52	13	52	52	16	16	52	18	26	52	52
WAG	r	1	.41	.23	.01	.34	.54**	.23	-.11	.27	.26	.21
	p		.10	.08	.91	.12	.00	.08	.59	.30	.05	.10
	N	56	16	56	56	22	22	56	22	16	54	56
RG	r	1	. ^a	.12	.05	-.27	.23	.24	.38*	. ^a	.37**	.24
	p		.	.37	.71	.10	.16	.07	.02	.	.00	.07
	N	54	0	54	54	36	36	54	36	0	54	54

Abbreviations: **. Correlation is significant at the 0.01 level and *.05 level.

The results in (Table 4) of t test women's artistic gymnastics between m.VM_Tc_R - m.VM_Tc_L were significant; t test (27) = 2.78, $p < .010$, Cohen's $d = .38$, effect size $r = .19$, indicates that there are significant differences between m.VM_Tc_R (19.37±2.20, $n = 28$) and the scores at the m.VM_Tc_L (18.55±2.02, $n = 28$). The effect size, r was small .19. The mean difference is 0.820. The results in (Table 4) of independent t test rhythmic gymnastics between m.VM_Tc_R - m.VM_Tc_L were significant; t test (26) = 3.58, $p < .001$, $d = .72$, $r = .34$, indicates that there are significant differences between m.VM_Tc_R (19.35±2.27, $n = 28$) and the scores at the m.VM_Tc_L (17.83±1.90, $n = 28$). The effect size, r was small .34. The mean difference is 1.517 (Fig. 1). **Table 4.** Correlations (r) between muscle pairs (Pearson's correlation coefficient) and t test differences in contraction time in milliseconds readings of right and left side body.

Muscles	Disciplines	Paired Correlations		Samples p	Paired Differences		t	df	p
		N	Corr.		Mean	SD			
m.BB_Tc_R -	MAG	13	.46	.10	.86	3.30	.94	12	.36
m.BB_Tc_L	WAG	8	.31	.45	-.12	3.07	-.11	7	.90
m.TB_Tc_R -	MAG	13	.12	.67	.78	2.47	1.13	12	.27
m.TB_Tc_L	WAG	8	.80	.01	.35	1.44	.68	7	.51
m.BF_Tc_R -	MAG	26	.33	.09	.05	5.41	.05	25	.95
m.BF_Tc_L	WAG	28	.51	.00	-.88	4.55	-1.02	27	.31
	RG	27	.71	.00	.72	4.83	.78	26	.44
m.ES_Tc_R -	MAG	26	.83	.00	.25	1.01	1.31	25	.20
m.ES_Tc_L	WAG	28	.78	.00	.15	.92	.86	27	.39
	RG	27	.77	.00	.10	.90	.59	26	.55
m.GL_Tc_R -	MAG	8	.67	.06	.64	1.81	1.00	7	.34
m.GL_Tc_L	WAG	11	-.05	.87	-2.15	4.22	-1.69	10	.12
	RG	18	-.00	.97	-.50	3.84	-.56	17	.58
m.GM_Tc_R -	MAG	8	.10	.80	-.41	2.52	-.46	7	.65
m.GM_Tc_L	WAG	11	.86	.00	.14	2.37	.20	10	.84
	RG	18	.30	.21	.32	2.79	.49	17	.63
m.RF_Tc_R -	MAG	26	.70	.00	-.08	2.57	-.16	25	.86
m.RF_Tc_L	WAG	28	.63	.00	-.66	2.66	-1.31	27	.20
	RG	27	.40	.03	-.17	2.75	-.33	26	.74
m.TA_Tc_R -	MAG	9	.84	.00	-.69	1.20	-1.72	8	.12
m.TA_Tc_L	WAG	11	-.00	.97	.27	1.59	.57	10	.57
	RG	18	.61	.00	.43	1.62	1.14	17	.26
m.VL_Tc_R -	MAG	26	.63	.00	-.80	2.00	-2.03	25	.05
m.VL_Tc_L	WAG	27	.43	.02	-.18	1.83	-.53	26	.59
	RG	27	.54	.00	.06	2.00	.17	26	.86
m.VM_Tc_R -	MAG	26	.71	.00	-.16	2.11	-.39	25	.69
m.VM_Tc_L	WAG	28	.73	.00	.81	1.55	2.78	27	.01*
	RG	27	.45	.01	1.51	2.19	3.58	26	.00*

Abbreviations: * Correlation $p < 0.05$ level, ** 0.01 level, t = t test, df = Degrees of Freedom, *p, $p < 0.05$



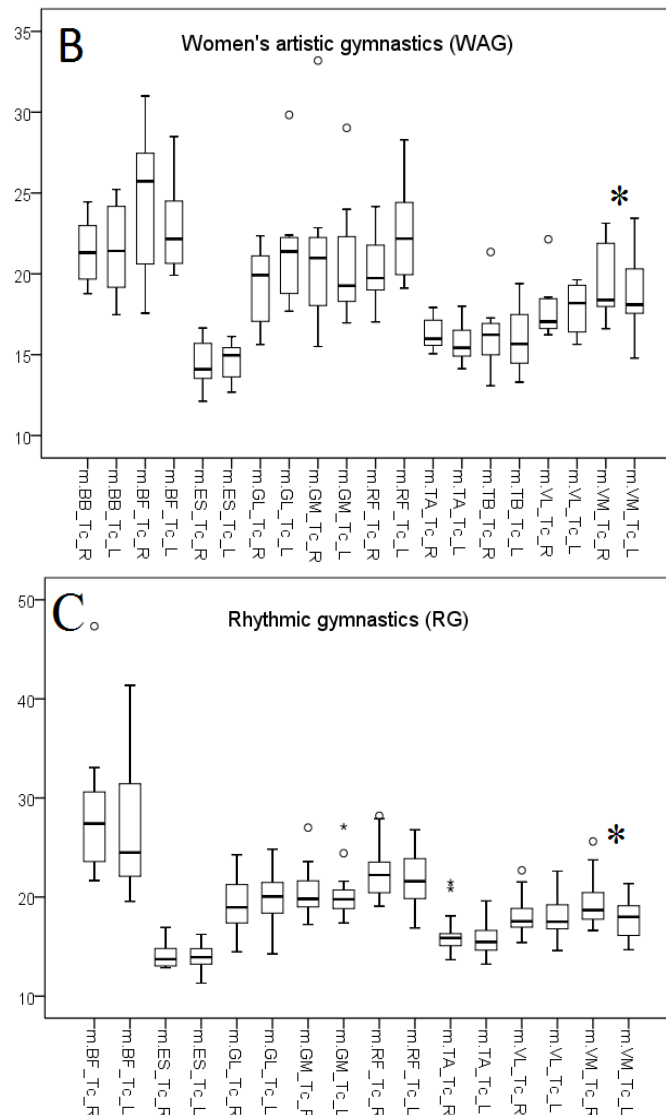


Fig. 1. Differences between skeletal muscle contractile parameters (Contraction time from 10% to 90% of maximal displacement) left and right body sides (A, MAG; B, WAG, C, RG).

Dicussion

The sample of athletes in the present study is representative for Slovenia and represents almost the whole population of MAG, WAG and RG gymnasts who take part in competitive sports. A characteristic of gymnastics is quick and explosive movements (Čuk & Karacsony, 2004; Atiković et al., 2015). Estimating contraction time values of fibres of skeletal muscles among MAG, WAG and RG gymnasts is therefore important. Contraction time is mainly correlated to the percentage of slow (type I) and fast (type II) muscle fibres and their metabolic, morphological and biomechanical features (Kirkendall & Garrett, 1998; Rogers & Evans, 1993; Strojnik, 2022).

The results in our study (Table 2) can be compared with the results of other authors from different sports. In a study of eight top dancers (average age 19.1 ± 3.6 years) it was found that the contraction time (m. BF: 34.2 ± 7.7 , m. ES: 18.3 ± 2.2 , m. GM 23.5 ± 2) was slower than the contraction times for the same muscles in gymnastics [44]. Šimunič & Samardžija (2015) established that gymnasts have on average quicker m. BB and m. TB muscles compared to footballers and volleyball players, a quicker m. BF muscle compared to footballers and volleyball players, and longer contraction times of m. BF compared to athletes⁴⁵. Longer contraction times (m RF 45.9 ± 16.2 and m BF 28.2 ± 5.2) were also found in professional bikers (Vuelta race) aged 27.5 ± 5.5 years (Garcia-Garcia, 2013).

Among gymnasts, the main difference was found between MAG and WAG in elbow flexors (m. BB), which are 3.5 ms or 14% slower in men (Table 2). The difference is likely seen because of the larger muscle

mass of arms and shoulders in MAG gymnasts compared to WAG gymnasts. On the other side, in RG (9%) and WAG (10%) m. BF is slower compared to MAG. In the literature no data about similar measurements from other countries were found. Our study is one of the first large studies to use the TMG measurement system in gymnastics. One case study of a top gymnast from Croatia was found. He was injured and with the use of TMG he obtained additional diagnostics. Based on the results, a corrective programme was designed, which he successfully completed and this allowed him to continue his basic training. He also obtained the best score for a floor event at the European championship in 2015.

Values of contraction time after the rehabilitation (when the gymnast was ready for 100% loading) were similar to the values of Slovenian gymnasts, except for m. GM which was slower in the Croatian athlete (43%) in comparison to Slovenian MAG gymnasts (Atiković et al., 2015). The results also allow us to define lateral symmetries, which represent a great problem in gymnastics. In addition to studies dealing with risks of injuries and rehabilitation programmes (Augustsson et al., 2004; Thomeé et al., 2012), one more specific analysis of COP of MAG and WAG was found, which warned about systematic asymmetries in gymnastics (Bučar, 2015), and an in-depth analysis of balance beam events where the trend of asymmetry in 60% of elements was found (Bučar et al., 2016). In high-level gymnastics, asymmetries have also been reported. Analyzing beam routines of the 2014 B World Cup, authors observed that the gymnasts initiated ~43% of their takeoffs and landings with the right lower limb, while the left lower limb was used to initiate ~30% of the actions; the remaining takeoff and landing actions were performed with both legs simultaneously. Only four out of 19 gymnasts loaded the left lower limb more often than the right, denoting a clear group preference for loading the right lower limb and using it to take off or land (Bučar et al., 2016).

Results of the conducted research in WAG the asymmetry does not exceed 10% (Table 3) and, according to the range of risks (Kirkendall & Garrett, 1998; Rogers & Evans, 1993; Sapega, 1990), it can be defined as a low-risk injury factor (low: up to 10%, middle: 10–20%, high: 20% and more). Higher asymmetry, which also means a bigger risk of injury, was found in WAG in m. GL (10%) and RG m. VM (9%). The risk of injury is increased primarily because of movement biomechanics, where the loading is greater on one extremity (Chavet et al., 1997), especially upon landing (Niu et al., 2011). Marshal et al. (2007) found that the majority of injuries in gymnastics happen on landing, and so it is clear why larger asymmetries increase the risk of injury. Bračić (2008) found that when one leg produces greater force on the ground during jumping, the body rotates in the frontal plane in the direction of the leg which produces less force, which has a negative impact on the effectiveness of the movement. Asymmetrical force production also affects the landing, where the leg which produced less force when jumping is overloaded (Bračić, 2010). Asymmetric jumps increase the risk of injuries on different body parts. Age has a negative impact on contraction properties of muscles in all observed disciplines. Dahmane (2006) made similar findings in elderly people as did Šimunić et al. (2014) among 9-year-old to 13-year-old children. The analysis of each gymnastics discipline shows there is a statistically significant correlation of slower contraction time and age among MAG in m. VM and m. VL, among RG in m. TA and m. VL and among WAG in m. GM (Table 4).

We assume that this could be correlated with the previously mentioned imperfections of the COP, where a strong and systematic focus on asymmetries was found (Bučar, 2015). Still, the finding is that ageing negatively affects the contraction time of muscles. This finding opens new possibilities for using the TMG method in the training of gymnasts and suggests the choice of exercise method which would aim at slowing down the negative effect of ageing on contraction times of muscles. For MAG, WAG and RG this would have a positive effect on both gymnasts' performances and the safety of the training. This study examined the association between contraction properties of muscles and jumping skill performance in gymnasts. 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 erector spinae muscle could indicate back problems and be indicative of inferior jumping performance in gymnasts. We agree with previous studies (Marinšek & Samardžija, 2020).

This study is the first larger study to use the TMG method and in which top athletes from artistic and rhythmic gymnastics participated. Considering the findings, it would be reasonable to use TMG as a method of analysis for comprehensively evaluating artistic and rhythmic gymnasts. It would add value to the synthetic (force plate) and partly analytic (isokinetic) measurement systems, which are already systematically used in artistic and rhythmic gymnastics. With use of TMG, we could improve the evaluation of gymnasts' condition and gain better insights into their risk of injury.

According to research, further studies define the normative values regarding the speciality of a gymnast because different movement structures and varying loadings on the body could impact on the results. Our study defined the framework of asymmetry considering the existing measurement systems. It would be reasonable to define the extent of the injury risk considering the established asymmetries and to adjust the ranges of risk to the TMG system. Tensiomyography has a high predictive ability to discriminate between injured and non-injured non-invasively and functionally (Santana et al., 2018). This study (Abazović et al., 2022) suggests that the TMG sensor is a sensitive tool to monitor PAP effects, and showed that Tc, estimated from the TMG response, is

shorter during the PAP, while it is not when estimated from torque twitch response. This study shows a typical example of injured and non-injured BF signals from the same subject. Comparing the Tc and Td of the injured subjects in the injured and non-injured BF muscles, statistically significant differences were found for Tc (all injured 32.9 ± 8.5 ms vs. all non-injured 24.6 ± 5.1 ms; $p < 0.001$) (Đorđević et al., 2022).

Conclusions

Muscle asymmetries in gymnasts are common and can lead to injury. Good balance and strength, body asymmetries are an important risk factor for injuries and may be associated with decreased performance. In artistic and rhythmic gymnastics, explosive power and strength endurance predominate. Jumps and landings are a basic part of daily training are often researched, typically using the force plate. In the future, TMG as an analytic method will hold an important place in sport diagnostics in gymnastics. With TMG, we can assess the discipline's demands and help improve gymnasts' performances along with the safety of training. Tensiomyography has a high predictive ability to discriminate between the left and right sides of the body functionally.

Conflicts of interest - The authors declare no conflict of interest.

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