MECHANICAL LOWER LIMB MUSCLE FUNCTION AND ITS ASSOCIATION WITH PERFORMANCE IN ELITE TEAM GYMNASTS

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Abstract

TeamGym (TG) differs from individual gymnastics as it is performed in teams including 6-12 participants competing in acrobatic performance in three disciplines: trampette jumping, tumbling track jumping, and floor exercises. The physical demands required by TG athletes largely remain unknown, and likely are dictated by the specific disciplines and equipment used. This study aimed at describing physiological capacity by investigating mechanical lower limb muscle function and its association with TG performance in 24 senior elite (12 males, 12 females) team gymnasts. Methods: Anthropometrical data as well as 25m sprint ability, repetitive jumps (RJ), countermovement jumping (CMJ), drop jumping from a height of 48cm (DJ_{48}), maximal isometric leg press muscle strength (MVC) and rate of force development (RFD) were measured. Results: Significant sex differences ($p<0.05$) were observed for all variables, except MVC. Total sprint times were 3.36 ± 0.1s in males vs. 3.70 ± 0.1s in females, CMJ height 0.51 ± 0.05 vs. 0.41 ± 0.03m, DJ_{48} rebound height 0.43 ± 0.06 vs. 0.34 ± 0.06m, with no difference in concentric peak power production between CMJ and DJ_{48}. MVC was 38.3 ± 9.9N/kg in males vs. 36.4 ± 9.2N/kg in females. In female gymnasts, correlations ($r^2=0.41$-0.46, $p<0.05$) were found between trampette and tumbling performance and sprint ability. In male gymnasts, correlations ($r^2=0.44$, $p<0.05$) emerged between trampette performance and relative RFD (%MVC/s). Conclusions: Moderate associations were found between mechanical lower limb muscle function and functional tumbling performance in male and female TeamGym, indicating that performance in elite TeamGym also relies on factors other than isolated mechanical muscle function.

Keywords: TeamGym, sprint, jumping, maximal strength, RFD, acrobatic performance.

INTRODUCTION

The sport of gymnastics comprises different disciplines like sports acrobatics, rhythmic sports gymnastics and artistic gymnastics. As a sub-discipline, TeamGym (TG) is becoming increasingly popular with European Championships conducted biannually since 1993 (Elbaek & Froberg 1993). In TG the gymnasts compete in teams of 6-12 gymnasts in 3 disciplines: 1) advanced acrobatics on the trampette, with and without vaulting table, 2) tumbling with both forward, and

backwards acrobatic routines, and 3) floor routine with dance elements, acrobatics, and choreography. The performances of the gymnasts are evaluated on basis of the difficulty and the quality of the acrobatic drills and the floor routine (Sjöstrand et al. 2015). The combined scores assigned to the 3 disciplines determine the final ranking of the teams.

Few scientific studies have investigated TG, most of them with a focus on common types and frequency of musculoskeletal injuries (Harringe et al. 2004; Harringe et al. 2007). In general, the acrobatic performance of gymnastics involves highly complex full-body movements and TG has been shown to induce substantial stress on the lower extremities (Harringe et al. 2004; Harringe et al. 2007; Lund & Myklebust 2011).

In an early study conducted in 1992, the year prior to the first European Championship, Elbaek & Froberg (1993) investigated the capacity of Danish club-level TG gymnasts. They concluded that TG athletes were characterized by superior anaerobic power and strength levels compared to a control group of physical education students. Since this early report, exercise equipment such as the tumbling track and the trampette has evolved considerably worldwide resulting in increased levels of difficulty of the acrobatic skills. Accordingly, an increased demand for high technical and physical capacity has been introduced in modern TG competitions.

Power generation, explosive-type movements and high anaerobic capacity are among performance-decisive factors across various gymnastic disciplines. (Elbaek & Froberg 1993; Bale & Goodway 1990; Jensen et al. 2013; Jemni et al. 2000; Suchomel et al. 2016; Aleksić-Veljković et al. 2016). However, these aspects have not previously been systematically examined in elite TG athletes. Therefore, the purpose of the present study was to describe the physiological capacity of international level TG athletes by examining mechanical lower limb muscle function (Power, MVC strength, RFD) and its associations to TG performance in Danish elite male and female team gymnasts. It was hypothesised that several of the test outcome would be related to TG performance among these athletes.

METHODS

The participants recruited for the study were senior gymnasts from the 2016 National Danish Teams (male, female and mix). Testing was performed prior to the Danish National Championship. Exclusion criterion was current musculoskeletal injuries to the back or the lower extremities. Participants were experienced in performing regular testing in their clubs or at National Team training camps. They gave their informed consent to participate in the test protocols and were well informed of the potential risks. A total of 12 male and 12 female team gymnasts completed the tests. Age, body height, body weight, body fat, training hours and TG performance are reported in Table 1.

Participants reported their current performance level in different acrobatically skills. The reported skills were divided into (i) trampette jumping and (ii) tumbling jumping. The international Code of Points (Sjöstrand et al. 2015) were used to rate the difficulty of performance (D-score) and the total score of the three most difficult skills in both trampette and tumbling were selected for analysis. Notably, the D-score has no upper limits. To the best knowledge of the authors, the highest scores for an individual skill in trampette or series of skills in tumbling recorded at any international championships (males) have been 2.35 and 2.9 points, respectively.

All participants were instructed to refrain from strenuous exercise 24 hours prior to testing. Participants received instructional videos and photos of the tests prior to testing, alongside written information about the test procedures. The tests were executed in the presented order.

All participants performed the tests barefooted wearing regular training clothes.

Body height was measured using a standard wall measuring scale and the nearest 0.5cm was registered (SECA, Hamburg, Germany). Body and fat mass were measured using bioelectrical impedance (Tanita MC-780MA Body Composition Analyzer, Tokyo, Japan).

Time to sprint 25m from a standing start with intermediate times recorded at 5, 10, 20m and 25m was assessed using an automatic photo cell-based timing system (Swift Performance SpeedLight Dual-beam, Wacol, Australia). The start of the sprint was initiated from a sensor placed on the ground at the 0m marking. Participnts warmed up for 5 minutes by graded running and were instructed to complete two sprints of ~80-90% of their maximal voluntary effort. Participants performed the test barefooted on a wooden floor. Participants performed one sub-maximal trial (~80-90% of maximal effort) running between the light gates to get familiarized with the equipment. Subsequently, participants performed three maximal trials, where they were instructed to pass the 25m markers as fast as possible. In case of continous improvement over the three trials, an extra trial was given. The test leader (OHH) provided strong verbal encouragement during all trials.

RJ was performed on a contact-mat (0.6 by 0.6m) (Swift Performance SpeedMat, Wacon, Australia) as previously described (Hérbert-Losier & Eriksson 2014). The test consisted of a series of jumps where the aim was to perform 10 continuous vertical jumps as high as possible using the shortest possible contact time. The test was performed with the hands placed on the hips and participants performed as many sub-maximal trials as desired before performing two maximal trials. First and final jump were excluded, leaving 8 jumps for analysis. Reactive strength index (RSI = jump height / contact time) was

calculated (Young 1995). The trial with the highest RSI was selected for further analysis.

CMJ was performed on a force plate embedded into the floor of the Lab (0.6 by 0.4m) (Kistler 9281 B, Amherst, US) as described in detail previously (Thorlund et al. 2008). The vertical ground reaction force signal (Fz) was digitally sampled at 1000Hz. Participants stood still on the force plate with their hands placed at their hips and then performed a smooth movement into a self-chosen depth, followed by a fast-upward movement resulting in take-off and a vertical flight phase (cf. Fig.2 in Thorlund et al. 2008). The participants performed a self-chosen number of familiarization trials maybe at ~80% of maximal effort before completing three CMJ trials at maximal effort. The trial with the highest jump was selected for analyses. Maximal vertical jump height of the Body Centre of Mass (BCM) and peak leg extensor power during the concentric take-off phase were calculated by second order integration of the Fz signal as described in detail elsewhere (Thorlund et al. 2008).

DJ_{48} was performed from a 0.48m elevated drop force plate (0.51 by 0.46m) (AMTI R6-1000, Watertown, MA) while landing on the Kistler force plate used for CMJ. The Fz signals from both the AMTI and Kistler force plates were synchronously digitally sampled at 1000Hz. The analytical approach regarding the dual force plate method has previously been described in details by Baca (1999). The Kistler force plate acted as the rebound surface, whereupon the participants performed a drop landing followed by a rapid rebound movement (CMJ) followed by a rebound flight phase and subsequently landing on the ground level force plate (Kistler). Maximal vertical BCM flight height and peak leg extensor power during the concentric rebound phase were calculated as described above for the CMJ. Participants performed a self-chosen number of

familiarization trials at ~80% of maximal effort and subsequently performed a minimum of three trials at maximal effort.

Maximal strength and rate of force development (RFD) of the participants' dominant leg were assessed using static leg press testing in a custom-built leg press device with a fixed footplate instrumented with piezoelectric force transducers (Kistler 9367/8 B, Amherst, US) (Caserotti et al. 2008). The force signal was digitally sampled at 1000Hz, and subsequently lowpass filtered by a digital fourth-order, zero-lag Butterworth filter using a cut-off frequency of 10Hz. The latter was carried out off-line using a custom-built MatLab macro (MatLab 15a. MathWorks, MA, US).

Participants were seated with their thigh in a horizontal position and the knee joint fixed at a 120° position (0° = full extension). Arms were crossed over the chest and the back kept straight during all trials. Following three submaximal warm-up trials, three trials were performed at maximal voluntary effort. Participants were instructed to produce as much force as possible and to reach maximal force output as fast as possible. Participants received real-time visual feedback of the force output and were verbally encouraged during all trials. If there were a variation of more than 5% between the two best trials, an additional trial was performed. The trial with the highest force output (maximal voluntary contraction, MVC) was selected for further analysis. Onset of contraction was defined as the instant when force production exceeded the baseline level force by 2% of the maximal force value. All trials with a visible initial countermovement were discarded from the analysis. Contractile rate of force development (RFD) was derived as the average tangential slope of the force–time curve (Δforce/Δtime) calculated in the time interval 0-30ms and 0-100ms relative to the onset of contraction (RFD_{30ms} and RFD_{100ms}). Additionally, relative RFD was calculated as RFD_{30ms} and RFD_{100ms} normalized to MVC to examine qualitative muscle properties during the initial phase of rising muscle force (Aagaard et al. 2002).

Statistical analysis was performed using SPSS 24.0. Sex difference was tested with an unpaired t-test along with a 95% confidence interval of the difference of means. Assumption of normality was tested using the Shapiro-Wilk test for each variable and Pearson's product moment correlation was used to examine potential relationships between selected tests variables and TG performance. Results are presented as mean ± standard deviation (SD) unless otherwise stated.

RESULTS

Differences between male and female TG athletes were noted for all variables. Males were 11% older, 8% taller, had a 19% greater body mass and 8% lower fat mass than the females. Further, male athletes demonstrated ~50% greater acrobatic difficulty scores than female athletes, despite no significant difference in overall training volume (Table 1).

During 25m sprint testing male TG athletes demonstrated 6-11% faster split-intervals along with 9.2% faster total sprint time compared to female athletes (Table 2). During RJ testing, males had 48% higher RSI than female participants. During stretch-shortening cycle (SSC) testing male TG athletes jumped 24% higher in CMJ accompanied by a 24% greater peak power per kg body weight and jumped 25% higher in the DJ_{48} accompanied by a 18% greater peak power per kg body weight compared to female athletes (Table 2). No sex differences emerged for MVC expressed relative to body mass or for absolute and relative RFD obtained during leg press testing (Table 2). One male participant was excluded in the MVC analysis due to corrupted data signals.

Table 1

Anthropometry and TG performance including P values and 95% confidence intervals of the difference between males and females.

	Male	Female	P	Difference of mean 95% CI
Age (years)	22.2 ± 2.3	20.0 ± 2.3	= 0.02	(0.3, 4.1)
Height (cm)	175.8 ± 5.5	163.0 ± 5.7	<0.001	(8.4, 17.3)
Body mass (kg)	73.3 ± 8.3	61.4 ± 5.8	<0.001	(6.1, 17.6)
Fat mass (%)	13.1 ± 3.0	21.0 ± 3.6	<0.001	(-10.5, 5.2)
Training volume (hours)	9.9 ± 2.6	9.7 ± 1.6	>0.05	(-1.5, 1.5)
Tumbling performance (p)	5.8 ± 0.6	3.9 ± 0.5	<0.001	(1.4, 2.4)
Trampette performance (p)	5.5 ± 0.4	3.7 ± 0.3	<0.001	(1.5, 2.1)

Table 2

Sprint performance and lower limb mechanical muscle function in male and female elite team gymnasts including 95% confidence intervals of the difference between males and females.

	Male	Female	P	Difference of means 95% CI
25 meters sprint test				
Sprint 5m (s)	0.84 ± 0.03	0.92 ± 0.04	<0.001	(-0.1, -0.04)
Sprint 10m (s)	1.57 ± 0.06	1.72 ± 0.05	<0.001	(-0.2, -0.1)
Sprint 20m (s)	2.79 ± 0.09	3.06 ± 0.07	<0.001	(-0.3, -0.2)
Sprint 25m (s)	3.36 ± 0.09	3.70 ± 0.09	<0.001	(-0.4, -0.3)
RJ				
RSI (height/contact-time)	195 ± 32	132 ± 36	<0.001	(36.1, 90.5)
CMJ				
Jump height (cm)	50.7 ± 4.5	41.0 ± 3.0	<0.001	(6.5, 12.9)
Peak power (W/kg)	58.9 ± 7.9	47.6 ± 6.1	<0.001	(5.7, 16.9)
DJ_{48}				
Jump height (cm)	42.7 ± 5.8	34.2 ± 6.1	<0.001	(3.5, 13.5)
Peak power (W/kg)	57.1 ± 4.0	48.3 ± 6.4	<0.001	(4.5, 13.0)
Isometric leg press test				
Peak MVC (N/kg)	38.3 ± 9.9	36 ± 9	>0.05	(-5.9, 9.8)
RFD_{30ms} (N/kg/s)	96.3 ± 27.3	86 ± 43	>0.05	(-18.7, 40.0)
RFD_{100ms} (N/kg/s)	117.3 ± 38,9	110 ± 56	>0.05	(-31.5, 46.6)
Relative RFD_{30ms} (%MVC/s)	253 ± 51	230 ± 79	>0.05	(-31.0, 76.9)
Relative RFD_{100ms} (%MVC/s)	309.0 ± 88.5	298 ± 112	>0.05	(-70.7, 93.69

Table 3
Correlation analysis of male and female team gymnasts' test variables and acrobatic performance.

	Male				Female			
	Total tumbling performance		Total trampette performance		Total tumbling performance		Total trampette performance	
Variables	*Pearson Correlation*	*P-value*	*Pearson Correlation*	*P-value*	*Pearson Correlation*	*P-value*	*Pearson Correlation*	*P-value*
Sprint 5m (s)	-0.065	0.842	-0.031	0.924	**-0.622**	**0.031**	**-0.638**	**0.026**
Sprint 10m (s)	-0.001	0.997	0.023	0.942	-0.515	0.087	**-0.672**	**0.017**
Sprint 20m (s)	0.143	0.657	-0.010	0.975	-0.431	0.162	**-0.680**	**0.015**
Sprint 25m (s)	0.221	0.489	-0.040	0.902	-0.377	0.227	**-0.672**	**0.017**
RJ (RSI)	0.113	0.726	-0.055	0.866	0.367	0.240	0.164	0.612
CMJ (cm)	-0.212	0.509	-0.105	0.745	0.099	0.759	0.416	0.178
CMJ (W/kg)	-0.314	0.320	-0.162	0.615	0.245	0.442	0.430	0.163
DJ_{48} (cm)	-0.417	0.177	0.162	0.615	0.054	0.867	0.451	0.141
DJ_{48} (W/kg)	-0.260	0.414	-0.031	0.923	0.204	0.525	0.515	0.087
Peak MVC (N)	-0.210	0.536	-0.348	0.295	0.416	0.179	-0.042	0.898
Peak force (N/kg)	-0.140	0.682	-0.342	0.303	0.408	0.188	-0.144	0.655
RFD_{30ms} (N/kg/s)	-0.198	0.560	0.088	0.798	0.476	0.118	0.125	0.698
RFD_{100ms} (N//kg/s)	-0.189	0.579	0.102	0.765	0.444	0.148	0.128	0.693
Relative RFD_{30ms}	-0.097	0.778	**0.663**	**0.026**	0.245	0.444	0.189	0.555
Relative RFD_{100ms}	-0.026	0.939	0.440	0.175	0.174	0.588	0.146	0.651

Group means ± SD. Abbreviation: RJ: Reactive Jumps; RSI: Reactive Strength Index, measured by a series of 8 jumps as the [mean jump height / mean contact time between each jump]; CMJ: Countermovement Jump; DJ_{48}: Drop Jump (drop height of 48cm); MVC: Maximal Volunteer Contraction; RFD: Rate of Force Development, defined as the rise in force over time in the early phase (0-100ms) of muscle contraction (ΔForce / ΔTime). Numbers in bold express a significant correlation ($P < 0,05$) between test variables and total tumbling performance and total trampette performance.

Associations between TG performance and mechanical muscle function

Female TG expressed moderate-to-strong relationships between trampette performance and sprint capacity evaluated at 5m ($r^2 = 0.41$, $p = 0.02$), 10m ($r^2 = 0.45$, $p = 0.01$), 20m ($r^2 = 0.46$, $p = 0.01$) and 25m ($r^2 = 0.45$, $p = 0.01$). Also, 5m-sprint split-time was correlated to females' tumbling performance ($r^2 = 0.39$, $p = 0.03$). In addition, a moderate-to-strong relationship was found between trampette performance and relative RFD_{30ms} in male TG athletes ($r^2 = 0.44$, $p = 0.03$).

DISCUSION

The aim of this study was to examining mechanical lower limb muscle function and its associations to TG performance in Danish elite male and female team gymnasts and we hypothesised that several of the test outcome would be related to TG performance. Moderate-to-strong associations were observed between sprint capacity or mechanical lower limb muscle function versus acrobatic performance in the present group of male and female elite TG athletes.

Anthropometrical characteristics

When comparing height and body mass to that of highly trained individual gymnasts, the present male and female TG appears to be taller, heavier and with a higher body fat percentage compared to gender matched individual gymnasts (Jemni et al. 2000; Aleksić-Veljković et al. 2016; Rodrígues et al 2010; George et al. 2013). Rodrígues and colleagues (2013) have previously reported senior male trampoline gymnasts to have a higher fat percentage and greater body mass compared to artistic gymnasts. It has been argued that a small body size in individual gymnastics is beneficial for competitive performance (Bale & Goodway 1990; George et al. 2013). The notion that TG athletes were considerable taller and heavier than reported for individual gymnasts may be explained by differences in equipment and specific performance disciplines between TG and individual gymnastics. Thus, the rebounding equipment in TG may allow the gymnast to use a relatively longer contact time than possible in individual gymnastics, which might be beneficial for vertical impulse generation when the body mass is greater than typically seen in artistic gymnasts.

Sprint capacity

TG gymnasts have a run-up distance of maximum 25m in order to accelerate to the horizontal approach speed needed for performing their acrobatic drills. The present group of TG gymnasts showed faster sprint split-times compared to athletes in intermittent sports like i.e. football, hockey, netball who also rely on high sprinting velocity (Tanner & Gore 2013), indicating that high anaerobic muscle power is important in TG. In TG, the surface of the trampette is normally set to an angle of 20-30° relative to horizontal, which makes it possible for the TG gymnast to effectively convert a high horizontal run-up speed into a high vertical speed in the take-off phase, in turn resulting in a long flight time and high vertical jump height. In theory, an increased run-up speed will lead to a greater vertical jump height, due to a gain in vertical take-off velocity. However, in real-life settings even highly experienced TG gymnast may not benefit entirely from maximal running velocity during the run-up. The gymnast must overcome the reactive force during the time of contact with the trampette prior to take-off. If the achieved approach velocity is too high, the gymnast may find it difficult to reach the preferred hip and knee joint angle position at the instant of eccentric-to-concentric SSC transition as well as at the instant of take-off, thereby not reaching optimal vertical height of the jump. Thus, it is unlikely for TG athletes to use their maximal sprint capacity. In contrast, in competitive team sports such as football and team handball the ability to repeat maximal sprints during a match generally is considered a highly important factor (Bangsbo et al. 2006).

Sprint capacity at 5, 10, 20 and 25m were moderate-to-strongly associated with trampette performance in female TG athletes, explaining 41-46% of the observed variance in TG scores. Further, a correlation between 5m sprint capacity and tumbling performance was observed in female TG athletes indicating that high acceleration capacity is important for executing drills with high difficulty in acrobatic performance, at least among females. Thus, gymnasts with a strong acceleration capacity may be able to obtain more optimal control of the magnitude and direction of the impact force vector exerted on the trampette throughout the take-off phase.

Vertical Jumping Capacity

Trampette jumping and tumbling drills are fundamental aspects in TG-training. To evaluate different aspects of jumping performance, a range of vertical jump tests were used in the present study such as CMJ, drop jumping (DJ) and reactive jumping (RJ). During CMJ testing

duration of the take-off is often longer than observed when performing rapid DJ from a given drop height (Bobbert et al.1986) and longer than in RJ where the athletes intend to achieve a short take-off time (<250ms) combined with a high vertical jump height. These different jump types may be used to indicate the ability of the gymnast to produce SSC muscle power. CMJ testing represents the simplest way to assess anaerobic SSC leg muscle power, while DJ testing also reflects eccentric power generation that transits into a rebound-jump movement while also monitoring the concurrent concentric power production for the lower limb extensors. RJ reflects the ability to repeat vertical jumping of maximal flight height using a short take-off time, which may be relevant for tumbling performance. During the present application of CMJ, male TG athletes demonstrated relative high jumping capacity (0.51m BCM flight height) accompanied by substantial amounts of maximal muscle power generation in the concentric take-off phase (59W/kg). Our female TG athletes showed corresponding values of 0.41m and 48W/kg, which seem substantially higher than previously reported by Donti and colleagues in female artistic gymnasts (0.30m and 40W/kg, respectively) (Donti et al. 2014). Also, in comparison to Danish male trampoline gymnasts, the present male TG athletes demonstrated greater vertical jump height during CMJ (Jensen et al. 2013). Further, when compared to a group of mixed athletes (ski jumpers, alpine and freestyle skiers, snowboarders, and gymnasts) (Hilfiker et al. 2007), the present male and female TG athletes were within the same range of maximal vertical jump height (~0.32-0.47m) and leg extensor peak power (~45-65W/kg). This comparison indicates that TG athletes have relatively strong SSC jumping (CMJ) capabilities, which might be due to large amounts of TG training with focus on ballistic-type SSC movements.

The DJ_{48} test was chosen to simulate the impact and take-off phase in the trampette and the tumbling drills. Male and female TG athletes demonstrated reduced DJ rebound height (but not peak power production) compared with CMJ, which may not be surprising due to the high eccentric impact loads imposed on the leg extensor muscles during the deceleration and acceleration phases of the DJ (Young 1995; Tanner & Gore 2013). In the present study males and females jumped from the same drop height (0.48 m). Ideally, DJ height should have been individually adjusted in order to assess and compare the capacity for absorbing kinetic energy and impulse during the rebound phase to increase rebound-jumping height across different participants (Young 1995; Tanner & Gore 2013; Taube et al. 2012). Suchomel and colleagues (2016) previously investigated the DJ abilities of male elite junior artistic gymnasts (~15 years). Compared to these junior gymnasts (rebound-jump height ~0.30m), our male TG athletes showed a markedly higher rebound-jump height (~0.43m). When compared to elite male volleyball, basketball, soccer players and recreational athletes (drop jump rebound height ~0.32m) (Cappa & Behm 2013), male TG athletes also appeared to jump higher.

The RJ test was implemented to study the ability of rapidly transforming a landing to a take-off in a series of repetitive jumps, simulating performance in the tumbling discipline. It was hypothesised that team gymnasts would be comparable to track and field jumpers, as jumping exercise of various forms comprise a large part in the training performed in TG. The reactive strength index (RSI) was calculated as the ratio between average jump height and take-off time (Young 1995). Surprisingly, compared to athletics, the present gymnasts demonstrated a 58% lower RSI compared to track and field jumpers, indicating that TG athletes are not equally explosive or powerful in the transmission

between landing and take-off compared to state-of-the-art athletes in this field. It is possible that the relatively soft equipment used in tumbling causing the gymnasts to get used to employing a longer contact time (>250ms) between successive landings performed in an acrobatic combination, compared to the contact times observed in track and field sprinting and high jumping (<250ms).

Maximal lower limb muscle strength and RFD

High maximal muscle force capacity would seem a desirable feature for elite TG gymnasts, due to the high take-off forces generated during the impact with the trampette and tumbling track prior to take-off, and the impact forces during the subsequent landing phase (McNitt 1993). The present male TG athletes demonstrated MVC values that were comparable to that observed in newly drafted males prior to initiation of military training (age 20 years, height 175cm, force 2884N) (Asmussen & Heebøl-Nielsen 1961). The present group of female TG athletes had MVC values that were slightly higher than previously reported in female students (age 20 years, height 165cm, force 2099N) (Asmussen & Heebøl-Nielsen 1961).

MVC-normalized RFD (%MVC/s) represents a measure of the athlete's ability to express the maximal force-generating capacity in an explosive movement (Maffiuelti et al. 2016). This ability appears to be enhanced in track and field power athletes (determined at 0-50ms from onset of muscle contraction) compared to non-athlete (Tillin et al. 2010). This difference could be an indication of qualitative adaptations in power athletes, who may be characterized by higher maximal motor unit discharge rates and elevated proportions of type II muscles fibres (Maffiuelti et al. 2016). These possible adaptations and inherent neuromuscular properties have been suggested to have important influence on

athletic performance (Tillin et al. 2010). In the present study, male TG gymnasts with superior performance in the trampette were also able to produce a relatively higher proportion of their maximal force capacity when evaluated in the most initial phase of muscle contraction (0-30ms). This early-phase RFD-component is likely important in the initial phase of trampette contact, due to the rapid extension of the knees and hips at the instant of contact. This rapid extension is performed to produce as much force as possible to produce a maximal reactive breaking impulse, to enable a maximal amount of elastic energy storage in the trampette for use (recoil) in the subsequent take-off phase.

In summary, female elite TeamGym athletes demonstrated moderate-to-strong associations between TG performance and sprint capacity while also positively related to relative rate of force development in male athletes. In addition, TG athletes showed high sprint capacity while also characterized by high muscle power production and performance outcome during selected jumping tasks indicating that high running velocity and superior power production may be important in elite TeamGym. However, as only moderate-to-strong associations were found, performance in elite TeamGym must also rely on factors other than isolated mechanical muscle function.

Limitations

The chosen test battery might not fully complete to detect which physiological factors might best describe the sport in team gymnasts. Sport specificity could be improved by using a more specific foot position during the unilateral strength test as most gymnastic skills are performed with both feet close together at take-off, and therefore the unilateral leg press test might not be the ideal test for performance in TG. Also, although the gymnasts were high skilled, the results might be improved by including familiarization trials. Another limitation would be, that only tests

involving lower body were included. Kaldas and colleagues (2017) showed a significant correlation between performance level in artistic gymnastics and a push-up test ($r^2 = 0.91$) as well as a pull-up test ($r^2 = 0.80$). In future studies of TeamGym, upper body strength is recommended to be included in the battery. As in studies with elite athletes, the number of participants is limited to the very best. However, the strength is, that these athletes are supposed to be representative for top best sport performance.

CONCLUSIONS

This study shows that team gymnasts should focus to reach a high vertical jumping capacity, accompanied by strong sprint and acceleration skills in order to improve the physiological and biomechanical basis for their TG performance. Accordingly, it is recommended that TG athletes become exposed to plyometric jump training as well as heavy resistance training to form a strong base of muscle strength and power capacity as a prerequisite for developing the specific acrobatic expertise involved in TeamGym performance.

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