Acta Kinesiologica 19 (2025) Issue.2
DOI. 10.51371/issn.1840-2976.2025.19.2.1

Original Investigation

Neuromuscular Profile of Top-Level Youth Taekwondo Competitors Assessed Through Tensiomyography - Croatian National Youth Taekwondo Team Example

Nino Sladic[a], Drazen Cular[a,c,d], Matej Babic[a,b], Ana Kezic[a], Toni Tomas[e], Damir Zubac[f,g]
[a]Faculty of Kinesiology, University in Split, Croatia
[b]Faculty of Kinesiology, University in Zagreb, Croatia
[c]Einstein, Startup for Research, Development, Education, Trade and Services, Split, Croatia
[d]European Institute for Talents, Education, Research & Development, Split, Croatia
[e]Taekwondo Club Marjan, Split, Croatia
[f]University Hospital Cologne, Internal Medicine 1, Center for Integrative Oncology, Cologne, Germany
[g]Science and Research Center Koper, Institute for Kinesiology Research, Koper, Slovenia

Purpose: This study aimed to investigate the neuromuscular profile of elite youth Taekwondo (TKD) athletes using tensiomyography (TMG) to assess lower-limb muscle contractile properties and estimate muscle fiber composition.
Methods: Seventeen members of the Croatian national junior TKD team (10 males, 7 females) participated in this cross-sectional study. Anthropometric characteristics and age at peak height velocity (APHV) were assessed, and TMG measurements were performed bilaterally on the vastus lateralis (VL) muscle to obtain contraction time (Tc), delay time (Td), sustain time (Tr), and estimated percentage of type I muscle fibers (MHC-I%). The average chronological age of participants was 16.3 ± 0.9 years, with an average APHV of 13.4 ± 0.7 years.
Results: Males were taller and heavier than females, and females showed earlier biological maturation. No significant differences were found between the left and right VL for Tc (21.5 ± 2.6 ms vs. 22.2 ± 2.8 ms; $P = .29$) or MHC-I% (15.4 ± 9.5% vs. 14.4 ± 11.7%; $P = .69$). However, a significant side-to-side difference was observed in Td ($t = 2.43$, $P = .03$), suggesting asymmetries in neuromuscular activation onset. Substantial intra-individual variability in MHC-I% distribution was also observed.
Conclusions: These findings provide novel insight into the contractile characteristics of adolescent TKD athletes and highlight the utility of TMG as a non-invasive profiling tool. The results may inform individualized training design, injury prevention strategies, and athlete development models in youth combat sports.
Keywords: talent identification, muscle fiber typology, elite athletes, biological maturation, non-invasive muscle assessment.

Introduction

Taekwondo (TKD) is a dynamic Olympic combat sport characterized by high-intensity striking techniques, with rapid and explosive kicks delivered with precision and speed[1,2]. Competitive TKD bouts consist of intermittent periods of intense activity, requiring athletes to execute technically demanding movements while simultaneously making split-second tactical decisions[3]. Given the sport's emphasis on lower-limb techniques, elite TKD athletes are expected to demonstrate high levels of neuromuscular coordination, anaerobic power, and reactive strength[4,5].

Previous research has shown that the predominant energy system used during TKD competition is the phosphagen (ATP-PCr) system, which supports short-duration explosive actions. The glycolytic system also plays a significant role during repeated high-intensity efforts across multiple rounds[6,7]. Accordingly, there has been a growing scientific interest in developing sport-specific and non-invasive tools for assessing neuromuscular and anaerobic performance in TKD athletes. However, the underlying muscle fiber composition that contributes to force production in this sport remains insufficiently explored, particularly in youth populations. Traditional methods such as muscle biopsy, although considered the gold standard, are invasive and ethically unsuitable for routine use—especially with adolescent athletes.

Hip muscle strength, particularly hip flexion and extension, is a key determinant of kick performance and competitive success in taekwondo[8]. Muscle force production capacity is important for taekwondo performance, not only at high contraction speed, but also at low speed. Elite TKD practitioners demonstrate high anaerobic performance, with peak power outputs of 14.7 W/kg in males and 10.1 W/kg in females during Wingate tests[9]. They also show superior neuromotor excitability and faster reaction times to sport-specific stimuli compared to non-athletes[10]. TKD athletes display higher levels of muscular strength, particularly in knee extensor muscles, compared to recreational athletes[11]. This aligns with findings that individuals with a higher percentage of fast-twitch fibers produce greater torque at higher velocities[12]. The intermittent nature of TKD competition, characterized by short bouts of maximum exercise, further supports the importance of fast-twitch fibers in this sport[9]. These findings collectively suggest that TKD athletes may indeed exhibit a predominance of fast-twitch muscle fibers. Although these findings hypothesize a predominance of fast-twitch muscle fibers in TKD athletes, empirical data to support this assumption remain limited due to methodological constraints.

Tensiomyography (TMG) has emerged as a valid, non-invasive method for assessing skeletal muscle contractile properties and estimating muscle fiber composition. TMG measures the radial displacement of the muscle belly in response to an electrically evoked twitch, producing several parameters—contraction time (Tc), delay time (Td), and maximal displacement (Dm)—that are associated with specific muscle fiber characteristics[13,14]. Shorter Tc values are typically linked to a higher proportion of fast-twitch (MHC-II) fibers, whereas longer Tc values are indicative of a greater presence of slow-twitch (MHC-I) fibers.

Over the past decade, TMG has been increasingly applied in sports science to evaluate neuromuscular function and monitor training adaptations. It has shown utility across various athletic populations, including soccer players[15], sprinters and distance runners[16], and patients recovering from anterior cruciate ligament (ACL) reconstruction[17]. Moreover, TMG has been validated for use in pediatric settings, allowing for safe, informative, and repeatable assessments of muscle function and maturation[18,19].

Despite its widespread application, data on muscle contractile properties and fiber composition in youth TKD athletes remain scarce. A recent review[20] emphasized the potential of TMG for estimating muscle fiber distribution (particularly %MHC-I) and highlighted its role in talent identification and the development of individualized training strategies in combat sports.

Beyond performance optimization, understanding muscle typology in youth athletes may have important implications for health and long-term athletic development. By tailoring training to an individual's neuromuscular profile, it may be possible to reduce injury risk, improve adaptation, and minimize burnout or early dropout from sport. This type of profiling may be especially valuable during adolescence, a period marked by rapid growth and large inter-individual variability in physical maturation.

Therefore, the primary aim of this study is to investigate the neuromuscular profile of elite youth Taekwondo athletes by using tensiomyography to evaluate lower-limb muscle contractile properties and estimate muscle fiber composition. These insights may inform individualized training interventions and support talent development in high-performance combat sport environments.

Methods

Participants

The sample consisted of 17 elite junior Taekwondo athletes (10 males and 7 females), all members of the Croatian national team. Athlete selection was based on performance rankings from three official national selection tournaments, including the National Championships. The elite status of the sample is further supported by their international achievements, including five medals (3 gold, 2 bronze) won at the Junior European Taekwondo Championships in November 2021. All participants held valid Taekwondo athlete licenses (GAL) and were free from musculoskeletal injuries, confirmed by medical clearance from a certified sports medicine physician. The research protocol was approved by the institutional Ethics Committee. Written informed consent was obtained from all participants and their parents or legal guardians.

Study design and methodology

Anthropometric data collection included body height (cm), body weight (kg), and sitting height (cm). Body height was measured using a Martin anthropometer (precision: .01 cm), and sitting height using a Holtain sitting table (precision: .5 cm). All measurements were conducted in the morning hours under standardized conditions in a sports hall. Participants refrained from food intake, large fluid consumption, physical activity, and sauna use for at least 24 hours prior to testing.

Maturity offset and age at peak height velocity (APHV) were estimated using the sex-specific regression equations[21]. Input variables included chronological age, sex, body height, sitting height, and body weight. The resulting APHV score indicates the number of years before or after the individual's peak growth spurt, serving as a proxy for biological maturity.

Contractile properties of the left and right vastus lateralis (VL) muscles were assessed using tensiomyography (TMG). Measurements were conducted with a digital high-precision displacement sensor (TMG-BMC Ltd., Ljubljana, Slovenia) positioned perpendicular to the muscle belly. Participants lay in a supine position with the knee fixed at 30° of flexion (0° = full extension), supported by foam padding to ensure standardized joint angles.

A single 1-ms rectangular electrical stimulus was delivered via self-adhesive electrodes (TMG-S2, TMG-BMC Ltd.) placed 5 cm proximal and distal to the measuring point. The stimulation intensity was gradually increased until maximal muscle displacement was reached. For each VL, two maximal twitch responses were recorded. The average values of contraction time (Tc) and maximal radial displacement (Dm) were used for further analysis. Measurements were performed according to validated TMG protocols[13,19].

The estimated proportion of type I muscle fibers (MHC-I%) was calculated based on the TMG-derived parameters time delay (Td), contraction time (Tc), and sustain time (Tr), using a previously validated multiple regression model[13].

Statistical analysis

All statistical analyses were conducted using Statistica 14.0 (TIBCO Software Inc., Palo Alto, CA) and Microsoft Excel (Version 16.43, Mac OS). Descriptive statistics (mean, minimum, and maximum) were computed for all variables, separately by sex. Paired sample *t*-tests were used to assess differences between left and right leg contractile properties. Effect sizes were calculated using Cohen's *d*. Statistical significance was set at $P < .05$.

Results

The results presented in Table 1 indicate an average chronological age (Age C) of the participants of 16.3 ± 0.9 years, with a narrower age range for females (16.3 ± 0.7 years) compared to males (16.3 ± 1.1 years). The average age at peak height velocity (APHV) was 13.4 ± 0.7 years, with females reaching this milestone earlier (12.9 ± 0.3 years) than males (13.8 ± 0.7 years). These data suggest that females in this study entered the accelerated phase of pubertal development earlier than males, which may influence their contractile properties.

In terms of anthropometric measurements, the average height of participants was 176.6 ± 9.6 cm, with males being taller (180.8 ± 9.7 cm) than females (170.8 ± 6.2 cm). The average body weight was 61.7 ± 13.4 kg, with males heavier (64.8 ± 14.9 kg) than females (57.1 ± 11.6 kg). These differences may reflect sex-based physiological characteristics and sport-specific adaptations in elite youth Taekwondo athletes.

Table 2 presents the comparison of TMG-derived contractile properties between the left and right vastus lateralis (VL) muscles. No significant differences were found for contraction time (Tc) between the left (21.5 ± 2.6 ms) and right (22.2 ± 2.8 ms) VL ($t = -1.09$, $P = .29$), nor for sustain time (Tr) ($t = .41$, $P =$

Table 1. Biometric characteristics and contractile properties of the m. vastus lateralis.

	MALE (*n*=10)				FEMALE (*n*=7)				OVERALL (*n*=17)			
Variables	**Mean**	**SD**	**min**	**max**	**Mean**	**SD**	**min**	**max**	**Mean**	**SD**	**min**	**max**
Age C (y)	16.3	1.1	14.9	17.7	16.3	0.7	15.2	17.0	16.3	0.9	15.0	17.7
AgeAPHV	13.8	0.7	12.4	14.8	12.9	0.3	12.4	13.3	13.4	0.7	12.4	14.8
H (cm)	180.8	9.7	169.9	195.6	170.8	6.2	161.9	179	176.6	9.6	161.9	195.6
W (kg)	64.8	14.9	46.5	89.6	57.1	11.6	40.8	74.1	61.7	13.4	40.8	89.6
TcL (ms)	21.4	2.6	17.7	27.0	21.6	2.9	15.6	24.2	21.5	2.6	15.7	27.0
TdL (ms)	24.0	1.9	20.2	27.5	23.8	1.5	21.1	26.0	23.97	1.7	20.2	27.5
TrL (ms)	14.1	3.7	8.9	19.1	36.9	41.6	9.51	102.9	23.5	28.1	8.9	103.0
TcR (ms)	22.5	2.1	19.4	26.4	21.8	3.6	17.0	28.8	22.2	2.8	17.0	28.8
TdR (ms)	22.8	2.1	19.7	27.1	23.4	1.51	21.9	25.4	23.1	1.9	19.7	27.1
TrR (ms)	24.0	20.8	8.2	81.6	14.7	4.0	9.9	20.3	20.2	16.5	8.2	81.6
$MHC1(\%)_L$	14.6	9.7	4.3	33.6	16.6	9.9	4.0	28.2	15.4	9.5	3.98	33.6
$MHC1(\%)_R$	14.8	12.4	3.1	44.4	13.9	11.5	1.7	37.5	14.4	11.7	1.7	44.5

.69), or estimated MHC-1% values (t = .40, *P* = .69). However, a significant difference was observed in time delay (Td), with higher values for the left leg (t = 2.43, *P* = .03, Cohen's *d* = .59), indicating a moderate effect size and potential lateral differences in neuromuscular activation onset.

Table 2. Differences between the contractile properties of the right and left leg.

Variable	T-value	*P*	Significant at alpha=0.05	Cohen's *d*
TcL vs TcR	-1.09	.29	*P*>.05	- .27
TdL vs TdR	2.43	.03	*P*<.05	.59
TrL vs TrR	.41	.69	*P*>.05	.10
MHC-1L vs MHC-1R	.40	.69	*P*>.05	.10

Legend: Tc - contraction time, MHC 1 – myosin heavy chain type 1, L – left leg, R – right leg. Effect size (Cohen's *d*).

The average MHC-1% values for the left and right VL were 15.4 ± 9.5% and 14.4 ± 11.7%, respectively. As shown in Figure 1, substantial intra-individual variability in MHC-1% distribution was observed, without a clear dominance pattern between the limbs. This heterogeneity likely reflects individual differences in maturation timing, training history, or possible sport-specific morphological adaptations.

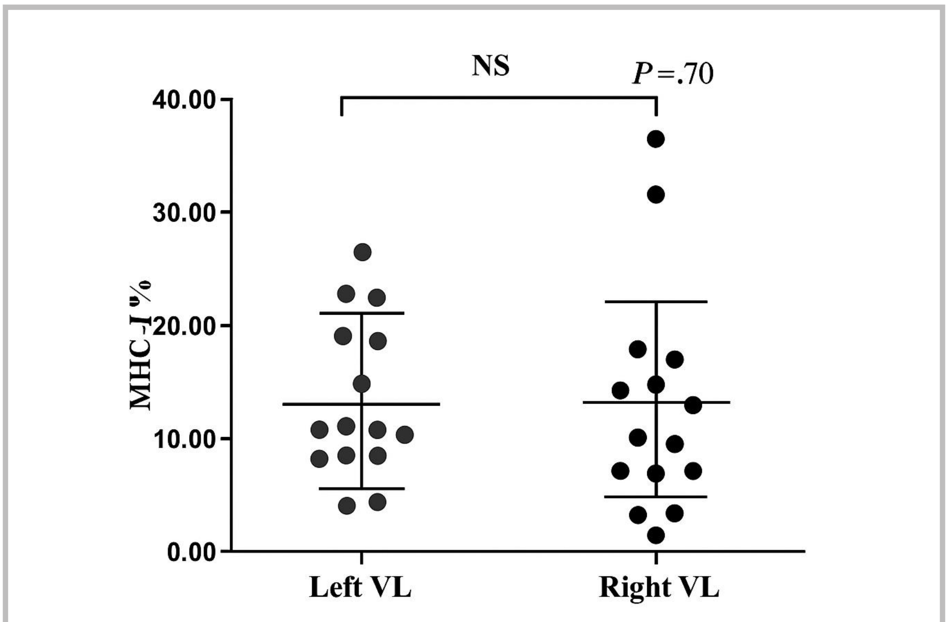

Figure 1. Intra-individual distribution of estimated MHC-I fiber proportion (%) between the left and right vastus lateralis (VL) muscles in elite youth Taekwondo athletes.

Discussion

The aim of this cross-sectional, comparative study was to evaluate the potential of tensiomyography (TMG) in assessing muscle contractile properties and estimating muscle fiber composition in elite youth Taekwondo (TKD) athletes from Croatia. The findings indicate no significant differences in TMG-derived contraction time (Tc) between the left and right vastus lateralis (VL), with average values of 21.5 ± 2.6 ms and 22.2 ± 2.8 ms, respectively. This symmetry may reflect the sport-specific demands of TKD, which emphasizes bilateral lower-limb activity due to the nature of kicking techniques and stance dynamics.

To the best of our knowledge, this is the first study to report Tc values in elite youth TKD athletes, which limits generalizability but provides a useful baseline for future investigations. These Tc values align with those found in adolescent track-and-field athletes, particularly sprinters and jumpers, whose Tc values average around 19.5 ms[19]. Such similarities support the notion that TKD places high demands on anaerobic and explosive strength capacities, consistent with the ATP-CP energy system dominance in competition.

Biological maturation also plays a crucial role in understanding contractile profiles. The average age at peak height velocity (APHV) in this study was 13.4 ± 0.7 years, with females reaching this milestone earlier (12.9 ± 0.3 years,) than males (13.8 ± 0.7 years,). This difference aligns with previous findings suggesting that biological age may be a more relevant predictor of physical and neuromuscular development than chronological age[22,23]. Although studies[24] found no significant effects of maturity status on TMG-derived contractile properties in elite youth soccer players, the influence of biological maturation in explosive, contact-based sports like TKD warrants further exploration.

Our findings on estimated muscle fiber composition revealed relatively low MHC-1% values (15.4 ± 9.5% for the left and 14.4 ± 11.7% for the right VL), suggesting a predominance of fast-twitch fiber characteristics. This is consistent with previous non-invasive and biopsy-based findings on adolescent and adult athletes[19, 25, 26]. Interestingly, we observed substantial intra-individual variability in MHC-1% distribution (Figure 1), which could be attributed to individual differences in maturation, training experience, or hereditary factors. Research[27] reported that contractile speed begins to increase markedly around age 12, particularly in boys, and continues to be shaped by sport-specific stimuli during adolescence.

Another potential source of variability lies in the TMG-derived variable Td, which is one of the components used in estimating MHC-1% and accounts for up to 87% of its variance. Differences in Td may reflect specific adaptations to TKD, such as dominant leg preference, stance type (guard), or technical style. In support of this, some authors[28] recently reported large intra-individual differences in muscle fiber composition in VL and gastrocnemius medialis, even when measured directly via biopsy.

Furthermore, genetic factors should not be overlooked. Evidence from twin studies[29] suggests a strong hereditary component in the morphology of the VL, vastus medialis, and rectus femoris. This supports the notion that TMG, when combined with genetic and maturational profiling, could enhance talent identification processes in elite youth sports. Nevertheless, several limitations must be acknowledged. The small sample size prevents firm conclusions regarding sex differences or broader generalizations. Additionally, measurements were limited to the VL; future research should include a wider range of lower-limb muscles, such as the vastus medialis, rectus femoris, and biceps femoris, to obtain a more comprehensive neuromuscular profile. In conclusion, this study highlights the applicability of TMG in evaluating neuromuscular function in elite youth TKD athletes. The observed contractile properties and fiber-type estimates suggest sport-specific adaptations and underline the need to consider biological maturation and inter-individual variability. Future longitudinal studies with larger, sex-balanced samples are essential to further understand the interaction between training, maturation, and muscle function during critical phases of athletic development.

Practical applications

The present study demonstrates that tensiomyography (TMG) is a practical, reliable, and non-invasive tool for assessing neuromuscular characteristics in elite youth Taekwondo athletes. The observed low values of MHC-I% and the substantial intra-individual variability highlight the importance of individualized profiling when designing training programs for adolescent combat sport athletes. Practitioners can use TMG-derived parameters—particularly contraction time (Tc) and delay time (Td)—to infer muscle fiber composition and monitor adaptations to explosive or hypertrophic training stimuli. From a performance standpoint, athletes with a higher proportion of fast-twitch fiber characteristics, as inferred from TMG, may benefit from power- and velocity-oriented training regimens, while those with a slower contractile profile might require a greater focus on neuromuscular activation and rate of force development. Furthermore, repeated TMG assessments across different maturational stages can assist coaches in identifying neuromuscular imbalances or asymmetries that may predispose youth athletes to overuse injuries. In a talent identification context, early detection of specific neuromuscular traits may inform long-term development pathways, enabling better alignment between physiological profiles and sport-specific demands. Additionally, incorporating TMG into routine monitoring can support return-to-play decisions, load management, and maturation-sensitive programming, which is particularly relevant in youth populations undergoing rapid growth and structural adaptation.

Conclusions

The data collected here indicate no significant differences in TMG-derived Tc readings between the left and right m. VL. Our findings extend beyond single-leg assessments, showing that MHC-1% values were similar between the left and right VL muscles. We also observed substantial heterogeneity in MHC-1% distribution, likely due to differences in maturation, sports experience, and probably genetic factors. Based on the findings, future research should include a larger sample of athletes across different age groups to further explore sex differences and the impact of growth stages on muscle fiber properties assessed through TMG. Additionally, it is recommended to extend the analysis to other lower limb muscles, such as the vastus medialis and rectus femoris, to provide a more comprehensive understanding of contractile properties in taekwondo athletes. The use of modern methodological approaches, including advanced imaging techniques and machine learning algorithms, could also enhance the accuracy of muscle fiber type estimation and improve talent identification processes and strengthen findings of this research.

Acknowledgments

The authors gratefully thank the athletes for their cooperation during the study.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Ethical Committee approval

The research protocol was approved by the Ethics Committee of the Faculty of Kinesiology, University of Split, Croatia (Approval No: 2181-205-02-05-20-006).

ORCID

Dražen Čular: 0000-0002-4370-2446
Ana Kezić: 0000-0002-9091-2761
Damir Zubac: 0000-0003-4204-4207
Matej Babić: 0000-0002-0911-5715

Topic

Sport Science

Conflicts of interest

The authors have no conflicts of interest to declare.

Funding

This research was supported by the Croatian Science Foundation under Project Grants No. [IP-2020-02-3366], No. [DOK-2021-02-8613] and No. [IP-2024-05-8340]. All grants contributed to different aspects of the study in compliance with the funding regulations.

Author-s contribution

Conceptualization, N.S and D.C.; methodology, A.K. and M.B.; software, D.Z.; validation, M.B. and A.K.; formal analysis, D.Z.; investigation, M.B, T.T. and D.C; resources, T.T., D.C.; data curation, N.S., A.K. and D.Z.; writing—original draft preparation, D.Z. and D.C.; writing— review and editing, N.S., A.K. and M.B.; visualization, A.K., T.T. and D.C.; supervision, D.Z., D.C. and A.K.; All authors have read and agreed to the published version of the manuscript.

References

1. Menescardi C, Falco C, Ros C, Morales-Sánchez V, Hernández-Mendo A. Technical-Tactical Actions Used to Score in Taekwondo: An Analysis of Two Medalists in Two Olympic Championships. *Front Psychol*. 2019;10:2708. doi:10.3389/fpsyg.2019.02708
2. Zheng AC, He CS, Lu CC, Hung BL, Chou KM, Fang SH. The Cognitive Function and Taekwondo-Specific Kick Performance of Taekwondo Athletes at Different Hydration Statuses. *Int J Sports Physiol Perform*. 2024;19(7):637-644. doi:10.1123/ijspp.2023-0332
3. Babic M, Marinovic M, Cular D. Anthropometric variability of European taekwondo champions. *Int J Morphol*. 2023a;41(2):612-617.
4. Ball N, Nolan E, Wheeler K. Anthropometrical, physiological, and tracked power profiles of elite taekwondo athletes 9 weeks before the Olympic competition phase. *J Strength Cond Res*. 2011;25(10):2752-2763. doi:10.1519/JSC.0b013e31820d9f3f
5. Moreira P, Franchini E, Ervilha U, Goethel M, Cardozo A, Gonçalves M. Relationships of the expertise level of taekwondo athletes with electromyographic, kinematic and ground reaction force performance indicators during the dollyo chagui kick. *Arch Budo*. 2018;14.
6. Baker JS, McCormick MC, Robergs RA. Interaction among Skeletal Muscle Metabolic Energy Systems during Intense Exercise. *J Nutr Metab*. 2010;2010:905612. doi:10.1155/2010/905612
7. Apollaro G, Ouergui I, Rodríguez YQ, et al. Anaerobic Sport-Specific Tests for Taekwondo: A Narrative Review with Guidelines for the Assessment. *Sports*. 2024;12(10):278. doi:10.3390/sports12100278
8. Moreira PVS, Falco C, Menegaldo LL, Goethel MF, de Paula LV, Gonçalves M. Are isokinetic leg torques and kick velocity reliable predictors of competitive level in taekwondo athletes?. *PLoS One*. 2021;16(6):e0235582. doi:10.1371/journal.pone.0235582
9. Heller J, Peric T, Dlouhá R, Kohlíková E, Melichna J, Nováková H. Physiological profiles of male and female taekwon-do (ITF) black belts. *J Sports Sci*. 1998;16(3):243-249. doi:10.1080/026404198366768
10. 1Chung P, Ng G. Taekwondo training improves the neuromotor excitability and reaction of large and small muscles. *Phys Ther Sport*. 2012;13(3):163-169. doi:10.1016/j.ptsp.2011.07.003
11. Martínez Hernández LE, Pegueros Pérez A, Ortiz Alvarado A, Del Villar Morales A, Flores VH, Pineda Villaseñor C. Valoración isocinética de la fuerza y balance muscular del aparato extensor y flexor de la rodilla en taekwondoines [Isokinetic evaluation of the muscular strength and balance of knee extensor and flexor apparatus of taekwondo athletes]. *Gac Med Mex*. 2014;150 Suppl 3:272-278.
12. Gregor RJ, Edgerton VR, Perrine JJ, Campion DS, DeBus C. Torque-velocity relationships and muscle fiber composition in elite female athletes. *J Appl Physiol Respir Environ Exerc Physiol*. 1979;47(2):388-392. doi:10.1152/jappl.1979.47.2.388
13. Simunic B, Degens H, Rittweger J, Narici M, Mekjavic IB, Pisot R. Noninvasive estimation of myosin heavy chain composition in human skeletal muscle. *Med Sci Sports Exerc*. 2011;43(9):1619-1625. doi:10.1249/MSS.0b013e31821522d0
14. Zubac D, Simunic B. Skeletal Muscle Contraction Time and Tone Decrease After 8 Weeks of Plyometric Training. *J Strength Cond Res*. 2017;31(6):1610-1619. doi:10.1519/JSC.0000000000001626
15. Buoite Stella A, Galimi A, Martini M, Di Lenarda L, Murena L, Deodato M. Muscle Asymmetries in the Lower Limbs of Male Soccer Players: Preliminary Findings on the Association between Countermovement Jump and Tensiomyography. *Sports*. 2022;10(11):177. doi:10.3390/sports10110177
16. Pakosz P, Lukanova-Jakubowska A, Łuszczki E,

Gnoiński M, García-García O. Asymmetry and changes in the neuromuscular profile of short-track athletes as a result of strength training. *PLoS One*. 2021;16(12):e0261265. doi:10.1371/journal.pone.0261265
17. Maeda N, Urabe Y, Tsutsumi S, et al. Symmetry tensiomyographic neuromuscular response after chronic anterior cruciate ligament (ACL) reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(2):411-417. doi:10.1007/s00167-017-4460-7
18. Franchi MV, Sarto F, Simunič B, Pišot R, Narici MV. Early Changes of Hamstrings Morphology and Contractile Properties during 10 d of Complete Inactivity. Med Sci Sports Exerc. 2022;54(8):1346-1354. doi:10.1249/MSS.0000000000002922
19. 1Simunic B, Degens H, Zavrsnik J, Koren K, Volmut T, Pisot R. Tensiomyographic Assessment of Muscle Contractile Properties in 9- to 14-Year Old Children. *Int J Sports Med*. 2017 Sep;38(9):659-665. doi: 10.1055/s-0043-110679. PMID: 29359281.
20. Cular D, Babic M, Zubac D, et al. Tensiomyography: from muscle assessment to talent identification tool. *Front Physiol*. 2023;14:1163078. doi:10.3389/fphys.2023.1163078
21. Mirwald RL, Baxter-Jones AD, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc*. 2002;34(4):689-694. doi:10.1097/00005768-200204000-00020
22. Malina RM, Kozieł SM. Validation of maturity offset in a longitudinal sample of Polish boys. *J Sports Sci*. 2014;32(5):424-437. doi:10.1080/02640414.2013.828850
23. Fransen J, Bush S, Woodcock S, et al. Improving the Prediction of Maturity From Anthropometric Variables Using a Maturity Ratio. *Pediatr Exerc Sci*. 2018;30(2):296-307. doi:10.1123/pes.2017-0009
24. Padrón-Cabo A, Corredoira FJ, Lorenzo-Martínez M, González-Víllora S, Rey E. Tensiomyographic Assessment of Contractile Properties in Elite Youth Soccer Players According to Maturity Status. *J Hum Kinet*. 2023;87:71-80. doi:10.5114/jhk/161571
25. Loturco I, Kobal R, Kitamura K, et al. Predictive Factors of Elite Sprint Performance: Influences of Muscle Mechanical Properties and Functional Parameters. *J Strength Cond Res*. 2019;33(4):974-986. doi:10.1519/JSC.0000000000002196
26. Trappe S, Luden N, Minchev K, Raue U, Jemiolo B, Trappe TA. Skeletal muscle signature of a champion sprint runner. *J Appl Physiol (1985)*. 2015;118(12):1460-1466. doi:10.1152/japplphysiol.00037.2015
27. Webber CE, Barr RD. Age- and gender-dependent values of skeletal muscle mass in healthy children and adolescents. *J Cachexia Sarcopenia Muscle*. 2012;3(1):25-29. doi:10.1007/s13539-011-0042-6
28. Van de Casteele F, Van Thienen R, Horwath O, et al. Does one biopsy cut it? Revisiting human muscle fiber type composition variability using repeated biopsies in the vastus lateralis and gastrocnemius medialis. *J Appl Physiol (1985)*. 2024;137(5):1341-1353. doi:10.1152/japplphysiol.00394.2024
29. Babic M, Zubac D, Cular D. Heritability assessment of contractile properties: insight from monozygotic twins' national youth track and field champions. *Med dello Sport.* 2023b;76(2): 248-259. doi: 10.23736/S0025-7826.23.04270-9

Corresponding information:
Received: 22.05.2025.
Accepted: 26.05.2025.
Correspondence to: Ana Kezic, PhD
University: Faculty of Kinesiology, University in Split, Croatia, Nikole Tesle 6, 21000 Split, Croatia
E-mail: ana.kezic@kifst.eu