Comparative Analysis of Elbow Flexor Morphology, Physiology, and Performance Between Arm Wrestlers and Strength-Trained Athletes

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Abstract

Coletta, F, Cesanelli, L, Kamandulis, S, and Conte, D. Comparative analysis of elbow flexor morphology, physiology, and performance between arm wrestlers and strength-trained athletes. *J Strength Cond Res* 39(5): 579–586, 2025—This study aims to compare the morphological, performance, and physiological characteristics of the elbow flexors between arm wrestlers and strength-trained athletes. Nine national and international level arm wrestlers (age = 30.5 ± 7.7 years, body mass = 89.4 ± 7.5 kg, stature = 183 ± 7.3 cm, strength training experience = 12.7 ± 8.6 years, arm wrestling training experience = 4.8 ± 2 years) and 9 strength-trained athletes (age = 28.6 ± 4.6 years, body mass = 88.2 ± 15.4 kg, stature = 179.4 ± 5.8 cm, strength training experience = 11.3 ± 8 years) voluntarily participated in the study. Arm and forearm circumferences of the dominant upper limb were measured to assess the anthropometric characteristics. Moreover, morphological evaluations of the biceps brachii muscle and distal tendon thickness were conducted using ultrasound. Peak torque (PT) and rate of force development (RFD) were assessed using 2 elbow flexion maximally voluntary isometric contraction tests (test-1: 3 × 3 seconds; test-2: 3 × 20 seconds). During test-2, biceps brachii oxygenation levels were measured using near-infrared spectroscopy. Arm wrestlers exhibited greater forearm hypertrophy compared with strength-trained athletes ($p = 0.005$; effect size [ES] = 1.54; large), whereas no differences ($p > 0.05$) were found in arm circumference and biceps brachii muscle and tendon thickness (normalized by muscle thickness). In addition, arm wrestlers showed higher PT in both tests ($p < 0.05$; ES = moderate-to-large) and higher RFD only in test-1 ($p < 0.005$). Finally, a greater reduction in muscle oxygenation levels ($p = 0.025$; ES = 0.277; moderate) was found compared with strength-trained athletes. This study provides insights of the arm wrestlers' physiological and performance characteristics allowing coaches to design appropriate training sessions in this unique sport.

Key Words: arm wrestling, performance analysis, muscle architecture, oxygen saturation

Introduction

Examining the morphological characteristics of athletic populations is essential for a better understanding of the specific features of sports performance, enabling the development of effective training techniques and the continuous monitoring of an athlete's progress. The specific nature of exercise stimuli produces distinct physiological and morphological changes in the affected muscle-tendon unit. Such adaptations depend on the muscle contraction type (i.e., concentric, eccentric, isometric) (12,24), modality (i.e., ballistic) (18), and intensity (13). These adaptations manifest through changes in muscle fiber composition, connective tissue structure, cross-sectional area, pennation angle, myofilament density, and macro and microcirculation efficacy (17). Chronic exposition to sport-specific training, thus, well explains the different physiological and muscle morphomechanical profiles that characterize athletes from different sports (27).

Among strength sports, arm wrestling is a peculiar sport predominantly relying mostly on isometric contractions of the elbow flexors and narrow range of motion, differently from other sports such as powerlifting and bodybuilding, where repetitive concentric-eccentric movements over a wider range of motion may be preferred for strength and hypertrophy development (32). It should be considered that although the general physical preparation for arm wrestling is common to other strength sports like bodybuilding and powerlifting, in the sport-specific preparation, the training of the elbow flexors at submaximal and maximal loads performed at very narrow angles (i.e., 90, 45, 30°) is emphasized to mimic competition scenario (31). Therefore, considering the chronic exposure to specific training typologies for athletes competing in these sports, it is plausible that differences apply in morphological and performance measurements between arm wrestlers and other strength sports athletes. As a result, a more thorough examination of this topic is necessary.

The muscle morphological and architectural parameters have been shown to be influenced by strength training and to have a positive and direct impact on the sport-specific performance (27,33). For instance, when considering arm wrestlers, it has been shown that the forearm circumference was able to differentiate between national- and amateur-level arm wrestlers (34). Nevertheless, muscle circumferences were the only measurements previously studied in arm wrestlers, whereas, to the best of our knowledge, there is a lack of information regarding other muscle-tendon unit

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morphological characteristics such as muscle and tendon thickness. Specifically, there is limited literature on the muscles and tendon thickness directly involved in arm wrestling performance, such as the biceps brachii and its tendon. This gap in knowledge is relevant, as understanding these morphological characteristics can provide valuable insights for coaches to monitor the muscle-tendon unit's changes over time. Moreover, no studies have specifically analyzed the morphological differences in the biceps brachii and its tendon between arm wrestlers and athletes from other strength sports. Considering the different types of contractions among different strength sports, it is expected a different chronic adaptation in the morphological characteristics of the muscle and tendons involved, which could likely lead to different performance outcomes.

Rapid force production is another critical aspect to be considered for strength sport performance. The rate of force development (RFD) can be deemed one of the main performance measures to be assessed (19), which has been demonstrated to be positively influenced by maximal strength training (25) and the stiffness level of tendinous force-transmitting structures (5). However, research has shown that explosive-type muscle contraction is the most efficient in inducing maximal gains in rate of torque development (RTD) at contraction onset, regardless of the load used (19). Although this performance indicator, together with peak force values (peak torque [PT]), measured at elbow flexor level seems fundamental for arm wrestlers because of the high correspondence between the sport-specific action and the modalities used for the RFD test (i.e., flexing the upper limb as fast as possible producing the highest level of strength as possible), there is limited information in literature. A unique study (3) assessed the RFD in 3 professional arm wrestlers during 100-, 200-, and 300-ms intervals emphasizing that the dominant factor influencing explosive strength was the starting force, representing a substantial 75–92% of the overall explosive strength. This manifestation primarily occurred within the initial 200 ms, but, considering the low sample size, 4 subjects, further studies are warranted. In addition, to the best of our knowledge, no previous study was investigating the differences in early and late RFD between arm wrestlers and other strength sport athletes, which can provide interesting information regarding the adaptation from a performance standpoint for these sports.

Muscle oxygen supply and utilization is a crucial factor influencing strength performance and fatigue indicators (6). The use of near-infrared spectroscopy (NIRS) allows to delve into muscle oxygen saturation levels and muscle blood volume in situ (10). Indeed, NIRS devices have made possible to investigate the role and relationship between muscle oxygen saturation levels and fatigue at both central and peripheral level. To date, no research has investigated the biceps muscle oxygenation and deoxygenation during sustained maximal effort in the context of arm wrestling, which seems a crucial information to have a full understanding of the arm wrestling performance and design accurate training sessions. Therefore, the aims of this study were to analyze and compare the morphological (muscle and tendon thickness), performance (PT, RFD), and physiological (oxygen saturation level) characteristics of the biceps brachii muscle-tendon unit during isometric contraction in professional arm wrestlers and strength-trained athletes.

Methods

Experimental Approach to the Problem

The study used an observational, cross-sectional design to investigate morphological and performance characteristics of arm wrestler and strength-trained athletes. Subjects attended a single session in the laboratory, with each testing session lasting approximately 1 hour. At the beginning of the experimental session, subjects were familiarized with the equipment used to collect each dependent variable. Successively, subjects underwent various measurements in the following order: (a) anthropometric; (b) morphological; (c) performance; (d) physiological measurements (Figure 1). To ensure optimal performance during testing procedures, subjects were instructed to abstain from training for a minimum of 48–72 hours before the session and to refrain from alcohol and caffeine use and to keep a regular diet before the experimental session.

Subjects

Nine national and international level arm wrestlers (mean ± SD; age = 30.5 ± 7.7 years, body mass = 89.4 ± 7.5 kg, stature = 183 ± 7.3 cm, strength training experience = 12.7 ± 8.6 years, arm wrestling training experience = 4.8 ± 2 years) and 9 strength-trained athletes (age = 28.6 ± 4.6 years, body mass = 88.2 ± 15.4 kg, stature = 179.4 ± 5.8 cm, strength training experience = 11.3 ± 8 years) voluntary participated to the study after signing informed consent forms. Subjects in the strength-trained group were training on average 3–4 times per week, with exercise intensity ranging from 75 to 95% of their 1 repetition maximum in their core exercises (e.g., back squat, flat bench press, deadlift, etc.). Similarly, arm wrestlers trained 3–4 times per week, including one session focusing on technical aspects (i.e., table training) and the remaining sessions focusing on strength development in the gym using sport-specific exercises (e.g., back pressure, side pressure, biceps curl, cupping, etc.). The recruited arm wrestlers represent 9 of the 12 Lithuanian professional athletes competing in the European arm wrestling championship 2021. This research was approved by a local institutional review board (Lithuanian Sport University, NR MNL-SVA (M)-2022-470). Inclusion criteria were at least 3 years training experience for arm wrestlers and strength-trained athletes, respectively, without injuries involving the upper limbs in the 6 months prior testing, cardiovascular, pulmonary, or metabolic diseases and chronic joint pain. All subjects were right-handed (dominant arm).

Procedures

Anthropometric Measures. Subjects' body mass was measured using Tanita TBF-300 (Tanita, Corp., Tokyo, Japan), and their stature was measured using a stadiometer (KaWe person check, Stuttgart, Germany) to the nearest 0.1 centimeters while barefoot. After this, the anthropometric measures of the dominant upper limb were taken with subjects standing still, using a flexible, nonstretchable 1-m measuring tape, according to the recommendations of the American College of Sports Medicine (30). Measurements were collected to the nearest 0.1 cm as follows: arm circumference at the midpoint between the acromion and olecranon processes, and forearm circumference on the largest part of the forearm, over the bulk of the brachioradialis muscle.

Morphological Measures. Images of the biceps brachii muscle thickness (BMT) and biceps brachii distal tendon thickness (BTT) were obtained through a gray scale B-mode ultrasonography linear array transducer (10–15 MHz transducer, Echoblaster 128, UAB; Telemed, Vilnius, Lithuania) with images recorded

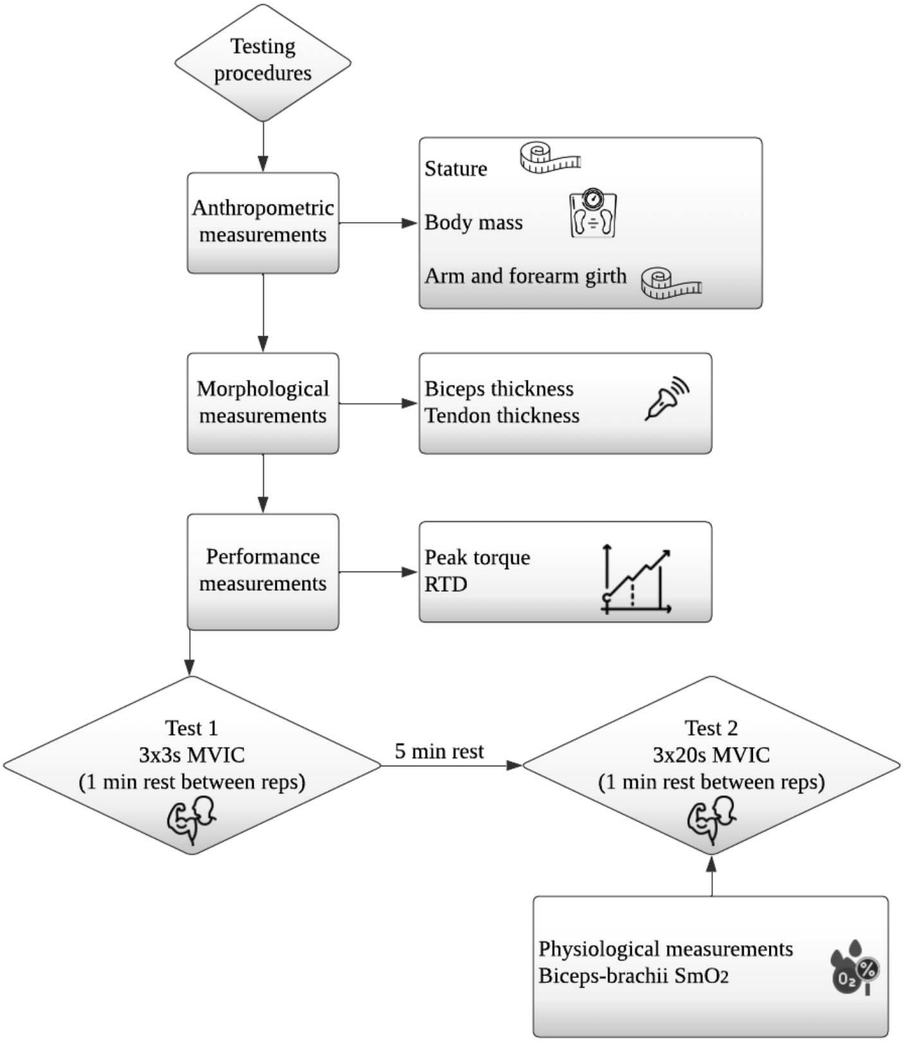

Figure 1. Study protocol flow diagram. MVIC = maximum voluntary isometric contraction; RTD = rate of torque development; SmO_2 = muscle oxygen saturation.

using the video-based software EchoWave II (Telemed). Measurements were carried out after the recommendations of the European Society of Musculoskeletal Radiology and previous research on ultrasound imaging application (22). Specifically, a water-soluble transmission gel was used to coat the transducer positioned over the subjects' skin with each subject sitting on a chair and the arm laying on an armrest for the measurements. For measuring BMT, the probe was positioned perpendicular to the tissue surface at two-thirds of the distance from the acromion to the antecubital crease, and minimal pressure was applied. The images of the ultrasound scanning were imported into the ImageJ software (v.1.46; National Institutes of Health, Bethesda, MD, USA) with analyses carried out according to the manufacturer's software recommendations. Three different ultrasound images of the biceps brachii (BB) muscle were recorded and averaged for subsequent analyses.

For the measurements of the BTT, the probe was positioned at the level of the elbow joint using the long axis oblique ulnar approach. Because the BTT has an oblique course from surface to depth, some artefacts might make the tendon appear hypoechoic because of anisotropy. Therefore, to overcome this problem, subjects were required to slightly bent their arm with the forearm in maximal supination to allow the tendon insertion on the radial tuberosity into view, maintaining the probe parallel to the tendon (2). The recorded images were subsequently imported into a video analysis software (Tracker, v.6.0.7, Open Source Physics, Aptos, CA, USA) with 3 measurements taken at a 5-10-15 mm distance from the tendon attachment onto the radial tuberosity and then averaged for the estimation of the BTT. Moreover, BTT data were normalized by BMT (BTT mm/BMT mm). All analyses were carried out by the same experienced rater, with the intrarater reliability measured before the commencement of the study on 4 separate occasions measuring the morphological measures on 2 active, male young adults with results revealing excellent reliability (BMT: intraclass correlation coefficient [ICC]: 0.97; coefficient of variation [CV]: 3.46%; BTT: ICC: 0.98; CV: 2.73%).

Performance Measurements. Before measuring maximum voluntary isometric contraction (MVIC), a standardized ~8-minute warm-up including biceps curls performed with a 17-kg straight barbell was adopted. Successively, subjects underwent 2 MVIC tests: test-1 was characterized by three 3-second repetitions, whereas test-2 encompassed three 20-second repetitions. The duration of test-2 was chosen based on the average duration of the semi-final and final rounds of the world arm wrestling tournament 2021, and it is in accordance with a study estimating an average match duration between 20 and 40 seconds (28). Both tests were interspersed by 1 minute of passive rest between the repetitions. The 2 tests were performed in succession with 5 minutes of passive rest in between to assure a full recovery and avoid any possible fatigue effects (Figure 1).

For each MVIC test, subjects were firmly strapped with 2 transversal shoulder-to-hip belts fixing the trunk to an isokinetic dynamometer (System 4; Biodex Medical Systems, Shiley, NY, USA). Subjects were also required to sit upright with the shoulder in 30° flexion, elbow 90° flexed, and forearm in a neutral position. The isokinetic dynamometer was rotated 30° away from the measuring arm, the chair rotated 0°, and a reinforced, custom-made handle was used. The dynamometer axis of rotation was aligned with the center of the trochlea and the capitulum of the humerus using visual inspection. The setting was further adjusted to ensure minimal trunk displacement during the maximal force exertion. Subjects were instructed to contract as fast and hard as possible on a given signal from the test supervisor, who provided constant verbal encouragement during the contraction phases to stimulate the maximum effort for the subjects.

For each MVIC test, the PT (Nm) was measured and considered as the maximum muscle strength. Contractile RTD was also calculated as the average slope of the torque-time curve ($N \cdot m^{-1} \cdot s^{-2}$) in the early (0–100 ms) and late contraction phase time intervals (0–200 and 0–300 ms). The onset of contraction was defined as the time point where the elbow flexor torque exceeded 2.5% of the baseline to peak isometric torque difference (19). Maximum voluntary isometric contraction, RTD0-100, RTD0-200, and RTD0-300 were averaged from the 3 repetitions of test-1, whereas they were analyzed singularly for test-2 to analyze whether changes occurred over time. The calculations were performed through a customized Excel spreadsheet using the raw data exported from the proprietary software. All tests were performed on the dominant limb and on the same day at the laboratory at a controlled temperature (21°). The dynamometer settings were provided by the Biodex manual (Biodex Multi-Joint System-Pro) available at the following link: https://www.biodex.com/physical-medicine/products/dynamometers/system-4-pro.

Physiological Measurements. Muscle oxygen saturation (SmO_2) represents the changes in the concentration of oxyhemoglobin [HbO_2] and deoxyhemoglobin. A NIRS device was used for muscle oxygen saturation monitoring of the BB in real-time (MOXY, Hutchinson, MO). The MOXY device calculates the relative concentration of HbO_2 in relation to the total amount of hemoglobin (tHb) (SmO_2 (%) = HbO_2/tHb) on a 0–100% scale (10). The device was placed over the midbelly of the biceps brachii muscle and was covered with a dark band to prevent light interference (23). The subjects were asked to stay relaxed for 2 minutes to establish the muscle oxygenation level at the baseline. Subsequently, although undergoing a 20-second elbow flexors MVIC test on the Biodex dynamometer, the instantaneous oxygen saturation levels were measured at the default sampling rate of 0.5 Hz. SmO_2 was analyzed through visual inspection of the oxygenation trend in the muscle. Two phases were identified: the execution phase, which represents the deoxygenation process happening from the start of the test and a descending slope characterizes it; the recovery phase, starting from the end of the muscle contraction and represented by an ascending slope in which reoxygenation of the muscle tissue is observed. Therefore, 3 variables were analyzed: maximal oxygenation value considered one second previous to the start of the muscle contraction (SmO_2max), minimum oxygenation level reached during the execution of the test (SmO_2min), loss of oxygen saturation (∇% SmO_2) represents the relationship between SmO_2max and SmO_2min (14), and it is calculated with the following formula:

$$\nabla\%SmO_2 = \left(\left(\frac{SmO_2 \times 100}{SmO_2max}\right) - 100\right) \times -1$$

Statistical Analyses

Descriptive statistics (mean ± *SD*) and median and interquartile range (IQR) were calculated for the dependent variables for arm wrestlers and strength-trained athletes. Shapiro-Wilk test revealed a normal distribution for most of the examined dependent variables except for BTT, RTD 0–100 ms, and SmO_2max. For the comparison between arm wrestler and strength-trained athletes of the normally distributed dependent variables, an independent *t* test was used after assessing the assumption of equality of variance (Levene's test). Differently, Mann-Whitney U test was conducted for BTT, RTD 0–100 ms (test-1), and SmO_{2max} to assess between-group differences. The analysis of RTD during test-2 was assessed using a 3 (repetition) × 3 (time) × 2 (group) mixed-model analysis of variance (ANOVA), whereas a 3 (repetition) × 2 (group) mixed-model ANOVA was performed for PT and SmO_2min. The assumption of sphericity was assessed using the Mauchly's test, and in case of violation, the Greenhouse-Geisser correction was applied. Moreover, in case of statistically significant differences, post-hoc analyses using Bonferroni correction were applied. Cohen's *d* effect size (ES) was also assessed and interpreted according to the following benchmarks: ≤0.20 trivial; small = 0.2–0.59; moderate = 0.60–1.19; large = 1.20–1.99; very large ≥2.0 (16). Moreover, partial eta-squared (η_p^2) was used as a measure of ESs for the 3 × 2 mixed model ANOVA and values were interpreted as no effect ($\eta_p^2 < 0.04$), minimum effect ($0.04 < \eta_p^2 < 0.25$), moderate effect ($0.25 < \eta_p^2 < 0.64$), and strong effect ($\eta_p^2 > 0.64$) (11). Finally, the *r*-value [Z/SQRT(N)] was adopted as ES for non-parametric statistics and interpreted according to Cohen's benchmarks considering 0.1, 0.3, and 0.5 as a small, medium, and large ES (8), respectively. Data analyses were carried out using Jamovi version 2.3.21 (https://www.jamovi.org). An alpha level of $p \leq 0.05$ was set to assess the statistical significance.

Results

Anthropometric and Morphological Measurements

Significant differences were not observed ($p > 0.05$) for age, body mass, stature, and strength training experience between arm wrestlers and strength-trained athletes (Table 1). Considering anthropometric measurements, a significantly greater forearm girth (centimeter) for arm wrestlers compared with strength-trained ($p = 0.005$; mean difference [95% CI]: 4.07 (1.43–6.71); ES: 1.54; large) was found (Table 1). In addition, although BMT and dominant arm circumference showed no differences between the investigated groups, arm wrestlers showed larger ($p = 0.024$, $r = 0.18$; small) BTT compared with strength-trained athletes (Table 1). Nevertheless, when considering for normalized values, no statistical difference emerged ($p = 0.444$) (Table 1).

Performance Measurements

The analysis of test-1 showed that arm wrestlers had a higher ($p < 0.005$) RTD measured at the various time points (0–100, 0–200, and 0–300 ms) and PT compared with strength-trained athletes

Table 1

Subjects' anthropometric and morphological characteristics stratified by sport discipline.*

Variable	Strength trained (n = 9)	Arm wrestlers (n = 9)	p
Age	28.6 ± 4.6	30.5 ± 7.7	0.541
Strength training experience (y)	11.3 ± 8.0	12.7 ± 8.6	0.718
Body mass (kg)	87.0 ± 14.8	97.0 ± 22.2	0.279
Stature (cm)	179.4 ± 5.8	183.0 ± 7.3	0.272
Right arm circumference (cm)	35.6 ± 3.5	37.9 ± 4.2	0.223
Forearm girth (cm)	32.5 ± 2.1	36.6 ± 3.0	**0.005**
Dominant arm BMT (mm)	35.7 ± 3.7	39.3 ± 7.2	0.196
Dominant arm BTT†	0.06 ± 0.01	0.06 ± 0.01	0.444

*BMT = biceps brachii muscle thickness; BTT = biceps brachii distal tendon thickness.

†Indicates a variable analyzed with nonparametric statistics, and values are presented as median ± IQR.

Statistically significant value is reported in bold.

with a large ES (Table 2). The analysis of RTD during test-2 indicated an effect for repetition ($p = 0.016$, $\eta_p^2 = 0.242$; minimum), time ($p < 0.001$; $\eta_p^2 = 0.843$; strong), and their interaction ($p < 0.001$; $\eta_p^2 = 0.340$; moderate), while no effect of group ($p = 0.287$; $\eta_p^2 = 0.071$; minimum). The post-hoc analyses are presented in Table 3. The analysis of PT indicated an effect for repetition ($p < 0.001$; $\eta_p^2 = 0.704$, strong) and group ($p = 0.018$; $\eta_p^2 = 0.303$; moderate), while no interaction was observed ($p = 0.098$). Post-hoc analyses revealed a higher PT in repetition-1 compared with repetition-2 ($p < 0.001$; ES = 1.38; large) and repetition-3 ($p < 0.001$; ES = 1.95; large), while no difference was found between repetition-2 and repetition-3 ($p = 0.259$) (Figure 2).

Physiological Measurements

The pretest analysis of the SmO$_2$max (i.e., 77.2% ± 6.43; 73.9% ± 4.35) was similar between groups ($p > 0.05$). The analysis of SmO$_2$min showed an effect for repetition ($p = 0.012$; $\eta_p^2 = 0.284$; moderate) and group ($p = 0.025$; $\eta_p^2 = 0.277$; moderate), while no interaction was observed ($p = 0.404$). Post-hoc analyses showed a greater reduction in SmO$_2$ in repetition-3 compared with repetition-1 ($p = 0.005$; ES = 0.64; moderate) and repetition-2 ($p = 0.05$; ES = 0.80; moderate) (Figure 3).

Discussion

This is the first study investigating the (a) anthropometric and morphological characteristics of the biceps brachii and its tendon, (b) force production, and (c) oxygen saturation levels during maximal isometric contractions in arm wrestlers and strength-trained athletes. The main outcomes revealed that overall, no differences emerged between arm wrestlers and strength-trained athletes in morphological aspects of the muscle-tendon unit. However, from a performance standpoint, arm wrestler denoted a higher explosive and maximal strength (RTD and PT, respectively) compared with strength-trained athletes and exhibited lower oxygen saturation levels during sustained maximal effort. The findings shed light on the specificities of arm wrestling training and its implications for musculoskeletal and physiological characteristics.

Interestingly, and in accordance with previous research (26), the findings of the current study confirm that arm wrestlers exhibited a notably larger forearm circumference in the dominant arm when compared with strength-trained athletes. This observation underlines the specificities of forearm muscle training in this sport. The increased forearm girth in arm wrestlers may be attributed to exercises on hand and forearm muscles during training, reflecting the tailored adaptations resulting from sport-specific training. In considering the musculotendinous structural profile, our findings show that despite expectations of higher hypertrophic structural remodeling, arm wrestling athletes did not exhibit significant differences in the biceps brachii muscle and tendon compared with strength-trained individuals. The understanding of how musculotendinous structures adapt to different forms of loading, whether concentric, isometric, or eccentric contractions, has been a subject of research (12,24) and have shed light on the different adaptations in muscles and tendons. However, there is still ongoing debate about whether the tendons dimension change in response to different mechanical stimuli (9). Furthermore, it seems that loading magnitude rather than contraction type specificity represents the main trigger for tendon adaptations such as growth and changes in material properties (4). Interestingly, despite the diversity in training modalities, significant differences were not observed between the 2 populations examined in our study, supporting the loading magnitude theory of tendon adaptations (4). This suggests that, despite different training modalities, the load applied to the elbow flexors may have been similar between the 2 studied populations. However, the specificity of training could have led to different alterations such as intrinsic tendon properties, particularly stiffness, rather than changes in thickness, explaining the differences in elbow flexors performance.

Table 2

Differences in performance measures between strength trained and arm wrestlers.*

Variable	Strength trained	Arm wrestlers	p	Mean difference (95% CI)	ES	Interpretation
RTD 0–100 ms (N·m^{-1}·s^{-2})	562 ± 124	720 ± 13.3	0.031		0.8	Large
RTD 0–200 ms (N·m^{-1}·s^{-2})	391 ± 15.2	522 ± 9	0.040	−131 (−256 to −6)	1.05	Moderate
RTD 0–300 ms (N·m^{-1}·s^{-2})	294 ± 8.7	374 ± 7	0.036	−80 (−155 to −5)	1.07	Moderate
PT (N·m^{-1})	107.2 ± 25.9	136.9 ± 27.2	0.031	−29.7 (−56.3 to −3.11)	1.12	Moderate
SmO$_2$min (%)	12.14 ± 5.9	5.31 ± 5.3	0.021	6.83 (1.17 to 12.5)	1.21	Large
∇% SmO$_2$†	83.33 ± 8.2	92.56 ± 7.4	0.024	−9.22 (−17.1 to −1.35)	1.17	Moderate

*RTD = rate of torque development; PT = peak torque.

†Indicates the mean % of the biceps brachii oxygen desaturation during test-2.

Table 3
Comparison of RTD between repetitions.*†

Variable	RTD 0–100 rep 1	RTD 0–100 rep 2	RTD 0–100 rep 3	RTD 0–200 rep 1	RTD 0–200 rep 2	RTD 0–200 rep 3	RTD 0–300 rep 1	RTD 0–300 rep 2	RTD 0–300 rep 3
RTD 0–100 rep 1	—	↑ $p = 0.025$; ES = 0.57, small	—	↑ $p = 0.001$; ES = 2.04, very large	↑ $p = 0.001$; ES = 1.58, large	—	↑ $p = 0.001$; ES = 2.35, very large	↑ $p = 0.001$; ES = 2.08, very large	↑ $p = 0.001$; ES = 2.09, very large
RTD 0–100 rep 2	—	—	—	↑ $p = 0.001$; ES = 0.97, moderate	↑ $p = 0.001$; ES = 1.69, large	↑ $p = 0.001$; ES = 1.36, large	↑ $p = 0.001$; ES = 1.58, large	↑ $p = 0.001$; ES = 2.03, very large	↑ $p = 0.001$; ES = 1.79, large
RTD 0–100 rep 3	—	—	—	—	↑ $p = 0.001$; ES = 1.03, moderate	—	↑ $p = 0.001$; ES = 1.42, large	↑ $p = 0.001$; ES = 1.74, large	↑ $p = 0.001$; ES = 1.81, large
RTD 0–200 rep 1	—	—	—	—	—	—	↑ $p = 0.001$; ES = 2.73, very large	↑ $p = 0.001$; ES = 1.41, large	↑ $p = 0.001$; ES = 1.50, large
RTD 0–200 rep 2	—	—	—	—	—	—	—	↑ $p = 0.001$; ES = 2.59, very large	↑ $p = 0.001$; ES = 1.55, large
RTD 0–200 rep 3	—	—	—	—	—	—	—	↑ $p = 0.001$; ES = 2.22, very large	↑ $p = 0.001$; ES = 3.02, very large
RTD 0–300 rep 1	—	—	—	—	—	—	—	—	—
RTD 0–300 rep 2	—	—	—	—	—	—	—	—	—
RTD 0–300 rep 3	—	—	—	—	—	—	—	—	—

*RTD = rate of torque development; ES = effect size.
†↑ indicates higher compared with the condition on top of the table.

Nonetheless, research has shown that sport-specific training can significantly impact performance outcomes, such as speed of contraction and maximal strength, through changes in the structure of muscles and tendons, which includes increasing stiffness, fascicle length, and elastic modulus (9). In this context, muscle dimensions and architectural features, influenced by sport-specific demands, appear to dictate alterations in torque or speed production capacity among athletes belonging to different disciplines (7). Furthermore, the mechanical properties of tendinous structures, including the tendon-aponeurosis complex, have been shown to respond to training specifics and can distinctly impact contractile and physical performance across various athletes (5,20). However, our study exclusively examines the elbow flexors, which, while critical for arm wrestling performance, may not encompass the most distinctive anatomical area compared with strength-trained athletes. It is conceivable that more pronounced differences could have emerged in

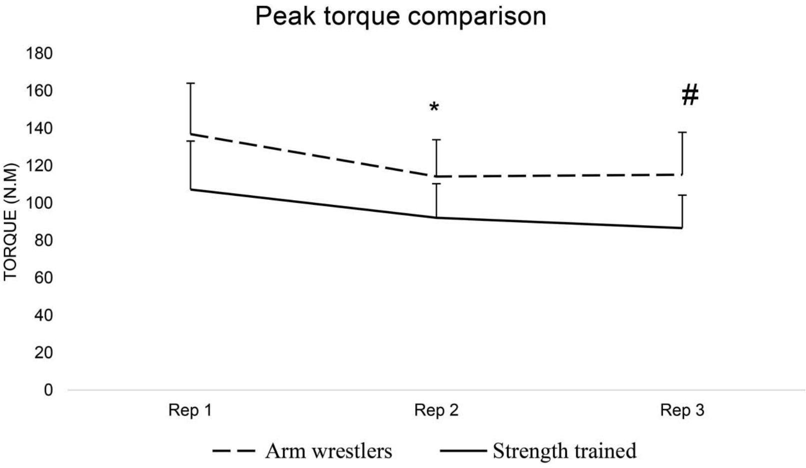

Figure 2. Comparison of arm wrestlers vs strength-trained peak torque (PT) during the 3 repetitions (rep 1, rep 2, rep 3) in 3 × 20 seconds maximum voluntary isometric contraction (MVIC) (test-2). *Indicates significant difference between rep 1 and rep 2 ($p < 0.05$), #Indicates significant difference between rep 1 and rep 3 ($p < 0.05$).

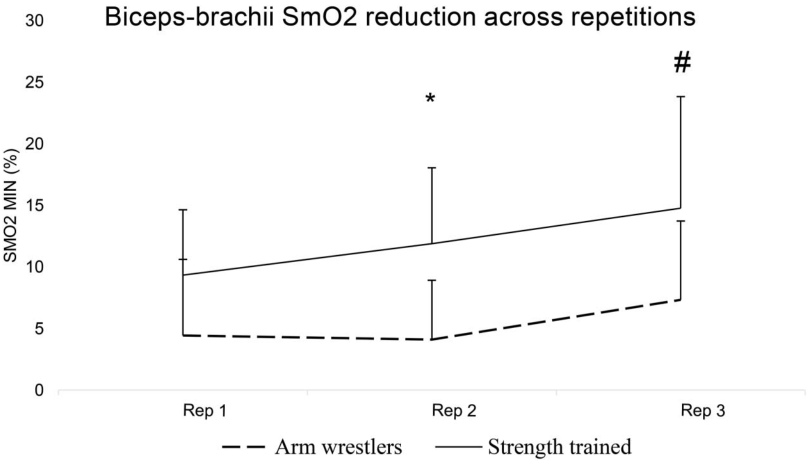

Figure 3. Comparison of arm wrestlers vs strength-trained minimum muscle oxygen saturation level (SmO_{2min}) during the 3 repetitions (rep 1, rep 2, rep 3) in 3 × 20 seconds maximum voluntary isometric contraction (MVIC) (test-2). *Indicates significant difference between rep 1 and rep 2. #Indicates significant difference between rep 1 and rep 3.

forearm and hand muscles and tendons. Nonetheless, these regions present challenges in terms of accuracy and repeatability when targeting morphological adaptive signatures (29).

Despite no difference in BMT and BTT, differences in performance emerged between the 2 groups, both in the maximum PT (test-1 and test-2) and in the 3 explosive force variables analyzed, RTD 100 ms, RTD 200 ms, and RTD 300 ms (test-1). The outcomes of our study highlight the higher explosive strength expression of arm wrestlers supporting the hypothesis that high RTD within the initial 200 ms of wrestling may significantly influence success in arm wrestling competition (3). Furthermore, our results likely reflect the training specificities and performance demands of arm wrestling competitions, and in turn the effect on neuromuscular adaptations (21). Even if we did not observe profound differences in morphological features of elbow flexors muscles and tendons, data on PT and RTD support the hypothesis that superior performance of arm wrestlers may be attributed to the increased forearm girth in their dominant arm and potentially to the higher tendon stiffness, which has been shown to be correlated with a higher force and power expression (5). The relationship between forearm size, elbow flexor strength, and hand-grip strength was also emphasized in previous studies (1,34) in which it was shown that professional arm wrestlers athletes display markedly higher forearm hypertrophy compared with amateur arm wrestlers suggesting its significance in influencing performance outcomes. Furthermore, the brachialis muscle, acting as the primary elbow flexor, exerts maximal force with the elbow in a neutral position. Therefore, arm wrestling athletes are likely to exhibit notable greater development in the brachialis muscle compared with strength-trained athletes. The higher development could potentially explain their superior performance in terms of PT and RTD. However, the RTD test-2 did not yield significant differences between the 2 groups. The increased difficulty of test-2 because of longer duration may have led the athletes to unconsciously regulate their force output, hindering their ability to express high levels or RTD.

To the best of our knowledge, this is the first study comparing the oxygenation capacity of arm wrestlers and strength-trained athletes. The groups did not show any significant differences in the maximal muscle oxygen saturation (SmO_2max) of the biceps before the start of the test-2. However, arm wrestling athletes achieved near-total deoxygenation during sustained maximal isometric contractions (92.56 $\nabla\%$ SmO_2) compared with strength-trained athletes (83.33 $\nabla\%$ SmO_2) and were able to exert higher level of force during the trials despite the onset of fatigue. The greater reduction in oxygenation levels may indicate improved vascular capacity and structural adaptation of conduit arteries. In this regard, previous studies have found that professional rock-climbing athletes, who regularly perform intense isometric contractions, experience notable changes in brachial artery size, capillary density, and microcirculation in their forearm muscles, and that the capacity of these athletes to deoxygenate and reoxygenate their muscles was higher during sustained contractions (17). When repeatedly contracting at maximum intensity, the muscle undergoes temporary local ischemia caused by the heightened pressure within the muscle causing a cascade of physiological processes in endothelial cells, initiated by a decrease in oxygen supply, which contributes to the remodeling of conduit arteries (15). In addition, transient muscular ischemia has been shown to enhance both the extraction and utilization capacities of muscle oxygen (17). Therefore, it is plausible to speculate that arm wrestling athletes possess an increased vascular capacity of the brachial biceps muscle and possibly an enhanced structural adaptation of the conduit arteries, which could be the consequence of repeated intermittent maximal isometric contraction and sport-specific training.

One notable limitation of this study is the relatively small number of subjects, with only 9 individuals per group, which warrants caution in extrapolating the results to broader populations. This is particularly relevant for studies involving elite athletic populations, such as the arm wrestlers in this study, where recruitment is inherently challenging because of the niche nature of the sport and the limited availability of athletes competing at such a high level. In addition, the assessment of PT and RTD was conducted using isometric exercises focusing solely on elbow flexion. It is also important to note that morphological evaluations were limited to the elbow flexors, and tendon mechanical properties such as stiffness or strain, which could have revealed further differences between the groups, were not analyzed. Moreover, arm wrestling performance involves a combination of movements like elbow flexion, supination, pronation, and side pressure among others. Therefore, future research could benefit from incorporating a more comprehensive assessment that reflects the multifaceted nature of arm wrestling movements. The neutral grip position in the torque assessments does not fully optimize the activation of the biceps brachii muscle, which exerts maximal force in a supinated position. Future studies could explore alternative testing protocols that better mimic the biomechanical demands of arm wrestling, include larger populations, consider a different group as control (e.g., subjects not involved in any competitive sport or exercise), and include more advanced technologies (e.g., magnetic resonance imaging) for the musculotendinous unit screening to provide a more comprehensive understanding of muscle function and performance in this sport.

Practical Applications

Despite the limitations, the findings of this study have several practical implications for athletes, coaches, and sports scientists involved in arm wrestling training and performance. First, the observed differences in forearm circumference and muscle oxygenation capacity underscore the need for targeted training strategies specific to arm wrestling. Coaches can design effective training programs that prioritize forearm strength and hypertrophy, and vascular capacity. In addition, the higher levels of explosive strength in arm wrestlers suggest the value of incorporating explosive, sport-specific isometric training to enhance performance, particularly in terms of RTD and PT of the starting position. Coaches should incorporate exercises targeting explosive strength and tendon stiffness into training routines to improve athletes' force generation during competition. Furthermore, periodic assessments of muscle oxygenation capacity can help monitoring vascular adaptations and optimize training interventions. These insights provide a foundation for evidence-based training strategies to enhance athletes' competitive success in this unique sport.

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