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Morphological and Mechanical Symmetry of the Quadriceps and Hamstrings in Athletes

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Featured Application: Musculoskeletal adaptation to between-sides sport.

Abstract: Sports performance can be influenced by several multifactorial conditions. Symmetries between sides can interfere with muscle strength, impacting performance. Balance in morphological aspects and muscle strength is desirable between dominant (DO) and non-dominant (ND) lower limbs to improve performance or to prevent injuries. The study aimed to compare quadriceps and hamstring muscle morphology and knee extensor and flexor torque while analyzing whether cross-sectional area (CSA) and echo intensity (EI) can better explain maximal concentric torque in competitive athletes. Sixteen competitive athletes of team sports were evaluated. Quadriceps and hamstring CSA and EI were assessed using a B-mode ultrasound. The maximal torque production capacity of the quadriceps and hamstrings was evaluated using an isokinetic dynamometer protocol. Our backward multiple linear regression models indicated that the quadriceps cross-sectional area (CSA) and echo intensity (EI) of the dominant (DO) and non-dominant (ND) limbs explain 61–79% of concentric torque production at 60°/s and 300°/s, with CSA showing a positive relationship and EI a negative one. Likewise, hamstrings CSA and EI account for 70–77% of torque production at the same angular velocities, both exhibiting positive relationships with torque output. Our data present bilateral mechanical and morphological symmetries in lower limbs of amateur athletes and potential predictive concentric torque capacity of CSA and EI for quadriceps and hamstrings.

Keywords: dominant and non-dominant limbs; symmetries/asymmetries; sports performance

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1. Introduction

Sports performance is influenced by several multifactorial conditions, but generally, muscular strength is one of the most important performance markers in many modalities and is influenced and modified by many aspects [1,2]. Among these, neuromuscular function and motor control play a crucial role in muscle performance, potentially altering strength production between limbs and influencing symmetry or asymmetry [3]. Assessing the balance between dominant (DO) and non-dominant (ND) limbs' muscle strength through morphological or functional evaluations is desirable for optimizing performance [4] and reducing musculoskeletal injury risk [5].

A strength imbalance of 10–15% or more between limbs and/or muscle groups can be considered problematic [6], as it is recognized as a risk factor for hamstrings injuries [7]. Such imbalances may arise from factors like asymmetrical loading patterns, commonly observed in sports that require single-leg jump tasks [8], as well as previous injuries and other intrinsic factors [4,9,10]. Discrepancies in muscle force production can lead to altered movement mechanics, increasing asymmetrical stress on musculoskeletal structures and elevating the risk of injuries [11].

The cross-sectional area (CSA) and echo intensity (EI) of muscle can be strong indicators of force-generating capacity [12]. Muscle CSA reflects the amount of parallel muscle tissue. Therefore, higher CSA is generally associated with a greater capacity to generate muscle force [13,14]. Quadriceps and hamstrings CSA are directly linked to muscle force production and performance in specific tasks and sports [14–21].

Although CSA is one of the most assessed morphological variables able to predict torque production capacity, it does not provide real measurements of the quantity of pre-sent contractile tissue [12]. Therefore, muscle quality assessed through EI serves as a valuable metric for quantifying muscle function using the gray scale index, where darker (black) areas indicate more contractile tissue, while lighter (white) areas indicate greater amounts of adipose and connective tissue [12,22]. Unlike CSA data, the present authors did not find any study using only EI as a dependent variable in regression models as a predictor of muscle force.

Some correlation models indicate considerable relationships between muscle quality (EI) and force production [23–26]. In middle-aged and elderly individuals, there is a significant correlation of EI with force production ($r = -0.4$), and when combined with muscle thickness, this could justify 29% ($r^2 = 0.29$) of muscle strength [24]. Furthermore, there are significant correlations between EI and isometric/concentric peaks of torque at 60, 180, and 360°/s (range from $r = -0.48$ to $r = -0.64$ and, respectively) [27]. However, Song et al. [28] found no relationship between upper (elbow flexors) or lower limb (knee extensors) EI and muscle strength. However, some limitations of these findings may be related to the failure to collect the total area of the muscle belly to quantify EI [29,30], the failure to normalize EI values based on subcutaneous adipose tissue thickness [31], and the failure to consider the effects of the penetration angle on the reflection of ultrasound waves, which can alter the tonal quality of the images [32].

In the sports context, evaluating and quantifying muscle symmetry is essential for optimizing performance and functional development, as muscular asymmetries can negatively impact performance and serve as indicators of musculoskeletal injury risk [5,10,11]. Additionally, understanding how muscle morphological parameters (CSA and EI) influence muscle performance may help elucidate new training strategies to maximize physical performance. Therefore, the primary objective of this study was to assess the symmetries of CSA, EI, and concentric torque (60°/s and 300°/s) of knee extensors and flexors between sides in competitive athletes of team sports. The secondary objective was to examine the relationship between the maximal concentric torque (60°/s and 300°/s) of knee extensors and flexors and the CSA and EI of the quadriceps and hamstrings muscles groups in these same athletes.

2. Materials and Methods

In this cross-sectional study, we aimed at the understanding of correlations between concentric torque (60°/s and 300°/s) of the knee extensors and flexors with the symmetries between the DO and ND limbs and whether the CSA and EI of quadriceps and hamstrings muscle determine maximal torque production capacity. Athletes visited the laboratory on a single day in which anthropometric data were previously measured. After 10 min

of rest, muscle morphology (CSA) and EI of both limbs were evaluated using ultrasound. Finally, the athletes were conducted to an isokinetic dynamometer in which they performed two maximal voluntary isometric contractions (MVIC) as well five concentric knee extension–flexion contractions at 60°/s and 300°/s. Our study was conducted according to the Declaration of Helsinki informed about the benefits and risks of the study before participating, and all procedures were approved by the local Institutional Research Ethics (number: 5.698.140). Before being evaluated, the athletes were instructed to avoid strenuous exercise and alcohol consumption in the last 48 h and not to consume caffeine or food during the 3 h prior to the evaluation. Exclusion criteria included chronic disease, smoking, metabolic disorders, use of steroids in the last one-year, chronic disease, physical disabilities, smoking, and use of antibiotic drugs in the previous week.

2.1. Participants

Sixteen competitive team sports athletes were evaluated, with the following characteristics: age: 22.1 ± 2.2 years; height: 176.6 ± 13.6 cm; body mass: 73.1 ± 13.1 kg; body mass index: 23.4 ± 2.8, as specified in Table 1. The athletes participating in the present study had 8.25 ± 5.06 years of regular training/competition and no history of musculoskeletal injuries of the lower limbs.

Table 1. Descriptive characteristics of the competitive team sports athletes.

	Athletes ♂♀(16)
Training (years)	8.25 ± 5.06
Age (years)	22.1 ± 2.2
Height (cm)	176.6 ± 13.6
Body Mass (kg)	73.1 ± 13.1
Body Mass Index (kg/m^2)	23.4 ± 2.8

2.2. Data Collection

Anthropometric data were measured according to the International Society for the Advancement of Kinanthropometry [33]. The body mass (kg) of the athletes was assessed using a portable electronic scale (Model PCS 180, Super Crown, Shangqiu, Henan, China) with a resolution of 100 g. Height was assessed using a tape (Single Fiber Tape Measure, Sanny, São Bernardo do Campo, São Paulo, Brazil) with a resolution of 1 mm. Athletes should wear light clothing and be barefoot for these measurements.

Initially, the subjects rested for 10 min, lying on a stretcher in supine position, with their lower limbs extended so that the body fluids could stabilize, avoiding interference in the images. After 10 min, the CSA and EI of the quadriceps and hamstrings muscles were assessed using a B-mode ultrasound system (ACUSON S2000; Siemens Healthcare, Mountain View, CA, USA) with a 9L4 linear array probe (40 mm, 8.0 MHz frequency), and the configuration for image acquisition was maintained the same for all subjects. Ultrasound images were captured in extended field of view (EFOV) mode by the same person, positioning the transducers at 50% of the proximal–distal length of the femur [34], transversely to the belly muscles. Two EFOV images were collected for each muscle group, in both limbs, resulting in four images per muscle group and eight images per subject.

Double-sided tape (3M™) was adhered transversely to the quadriceps or hamstring skin to serve as a side-rail for the probe to slide over the gel in the anterior and posterior regions of the thigh. The transducer was covered with a water-soluble transmission gel (to provide acoustic contact without depressing the dermal surface) on its distal surface, which was applied to the skin to obtain the images. A fixed configuration was used for all subjects in order to quantify the gray scale of the images with the following configurations of the ultrasound system (Frequency: 8.0 MHz; 80 mm image depth; 0 dB overall gain and time gain compensation in the neutral position).

After the ultrasonography protocol, data were collected using an isokinetic dynamometer (BIODEX, System 4 Pro™, Biodex Medical Systems, New York, NY, USA), which was calibrated according to the manufacturer's instructions. The subjects were seated at the dynamometer chair, adjusted to maintain 85° of hip joint flexion, and were attached with Velcro straps to provide stability during testing. The rotation axis of the dynamometer was aligned with the rotation axis of the tested knee joint (lateral femoral condyle). The lever arm was positioned to lower limb level, and a fixed-length pad was positioned 1 cm above the lateral malleolus.

The warm-up consisted of 20 submaximal knee extension–flexions at 120°/s. After a two-minute interval, subjects performed five maximal concentric contractions at 60°/s and 300°/s; extension and flexion were measured at in one movement sequence. The interval between each contraction adopted was two minutes. Before the beginning of each evaluation protocol, the evaluated velocities were randomized in order to avoid the effects of muscle fatigue on the torque production capacity. All assessments were performed on both DO and ND lower limbs, and the same two evaluators were responsible for verbal encouragement to ensure maximal effort from the athlete and protocol explanations.

2.3. Data Analysis

The ImageJ® software (National Institute of Health, Bethesda, MD, USA) was used to analyze the CSA and EI in the DO and ND lower limbs of the quadriceps and hamstrings muscles. The region of interest (ROI) was measured using the Polygon tool of the ImageJ® 1.54 software, covering the maximum CSA of each muscle group, quantifying the CSA and the gray-scale (EI), and avoiding the inclusion of the connective tissue of the aponeurosis at the edge of each muscle group, as shown in Figure 1. Muscle quality was quantified from the average of two frames, calculating the EI from the standard grayscale histogram function and expressed as a value between 0 (black) and 255 (white). All the images were analyzed by two independent analyzers, and the inter-investigator reliability of measurements was determined for the CSA and EI data. Averages were then calculated between the two analyzers for each variable for subsequent analysis.

Torque signals were recorded after gravity correction and sampled at 100 Hz using the dynamometer's software (Biodex, System 4 Pro™, Biodex Medical Systems, New York, NY, USA). The peak muscle torque of the knee extensor and flexor muscles was quantified from the five maximum concentric repetitions at the respective angular velocities (60°/s and 300°/s).

The inter-limb strength asymmetry was determined according to Chavet et al. [35], following Equation (1) [35]:

$$Asymmetry\% = \frac{DO - ND}{DO} \cdot 100 \quad (1)$$

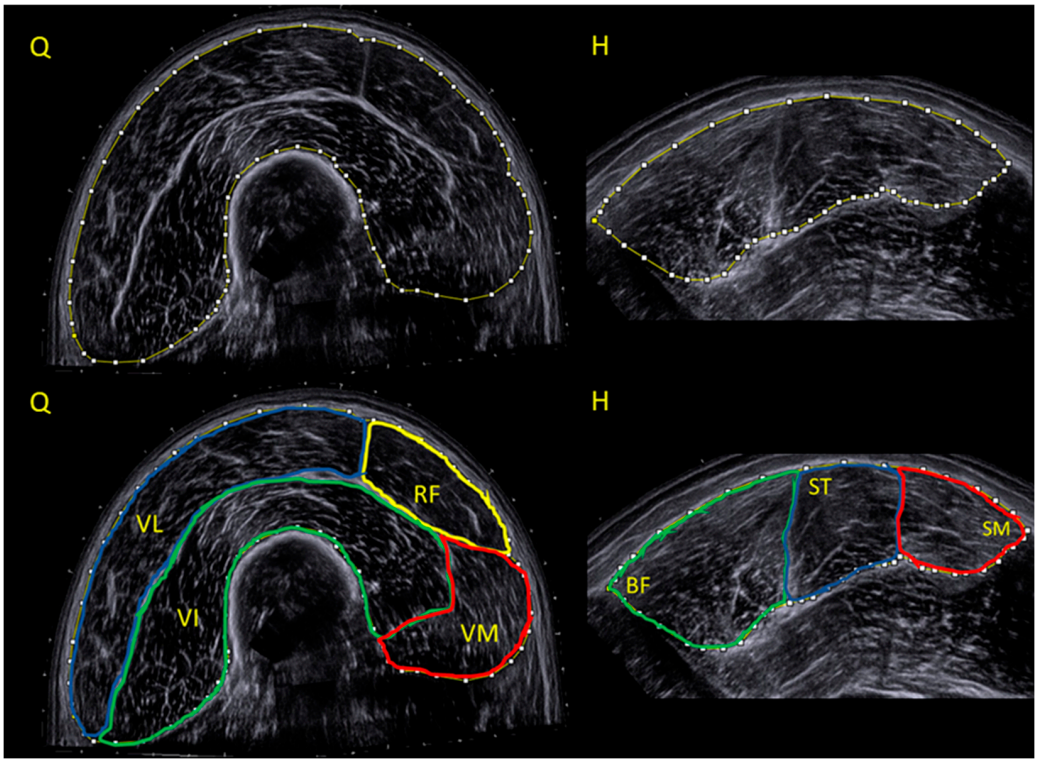

Figure 1. Illustration of the muscular architecture of the quadriceps (Q) and hamstrings (H). All the images show the cross-sectional area, with the Q indicating the vastus lateralis (VL), vastus intermedius (VI) indicated by the blue line, rectus femoris (RF) indicated by the yellow line, vastus intermedius (VI) indicated by the green line, and vastus medialis (VM) indicated by the red line. For H, we the biceps femoris (BF) with the green line, semitendinosus (ST) with the blue line, and semimembranosus (SM) with the red line.

2.4. Statistical Analysis

The normality and homogeneity of the data were assessed through Shapiro–Wilk, and Levene tests, respectively. Dependent sample t-test was used to compare all variables between sides. Simple linear regressions were performed in order to verify the relationship between sides for all the variables investigated. Cohen's effect sizes (ES) were computed for the analysis of the magnitude of the differences and rated as trivial (<0.25), small (0.25–0.49), moderate (0.5–1.0), and large (>1.0) [36]. Backward multiple linear regressions were used to estimate the relationship of dependent variables (torque at 60°/s and 300°/s) with the independent variables of (CSA and EI) of both sides of the quadriceps and hamstring muscle groups for DO and ND limbs. Our collinearity diagnostic analysis revealed variance inflation factors (VIF) below 2.0, indicating acceptable levels of multicollinearity among the independent variables [37]. In addition, the post-hoc power of the multiple linear regression was calculated according to Cohen et al. [38]. The ES of the multiple linear regression was calculated and classified as small (>0.02); moderate (>0.13); and large (>0.26) a priori using G*Power 3.1.9.7 as described by Faul et al. [39]. The correlation matrix showed the magnitude of the Pearson product–moment correlation coefficient between the dependent variables (knee extensors and flexors maximal torque) with the independent muscle variables (CSA and EI of quadriceps and hamstrings, respectively). The correlation was classified as negligible (r = 0.0–0.3); low (r = 0.3–0.5); moderate (r = 0.5–0.7); high (r = 0.7–0.9); and very high (r = 0.9–1.0) according to the thresholds recommended by Hinkle et al. [40]. All statistical analyses were carried out using SPSS 22.0 for Windows (IBM SPSS Inc, Armonk, NY, USA), with a significance level of $\alpha = 0.05$. All dataset is in Supplementary Material (Table S1).

3. Results

Descriptive characteristics such as sex, experience, age, height, body mass, and body mass index are summarized in Table 1.

Furthermore, Table 2 shows the comparisons between the DO and ND of team sports athletes for all variables ($p > 0.05$). Furthermore, ES between the lower limbs presented values between trivial and moderate for all evaluated variables (Table 2).

Table 2. Between-sides comparison for quadriceps and hamstrings muscle morphology and maximal knee extensor and flexor torque (dependent sample *t*-test).

Variables	Dominant	Non-Dominant	AI (%)	*p*-Value	t-Value	ES
CSA-Q (cm^2)	101.4 ± 32.9	100.7 ± 28.7	0.65	0.779	0.285	0.071
EI-Q (A.U.)	38.4 ± 6.2	37.1 ± 5.2	3.18	0.075	1.910	0.478
CSA-H (cm^2)	38.8 ± 10.4	39.0 ± 8.6	−0.62	0.794	−0.266	0.067
EI-H (A.U.)	47.0 ± 4.8	45.0 ± 6.0	4.34	0.118	1.660	0.415
T60-Q (N·m)	213.6 ± 52.3	218.5 ± 67.0	−2.26	0.530	−0.643	0.161
T300-Q (N·m)	134.1 ± 43.0	133.4 ± 43.1	0.50	0.826	0.224	0.056
T60-H (N·m)	111.1 ± 32.2	108.8 ± 34.6	2.08	0.378	0.909	0.227
T300-H (N·m)	94.8 ± 26.4	89.7 ± 26.3	5.37	0.059	2.042	0.510

AI: asymmetry index; ES: effect size; CSA-Q: cross sectional area of quadriceps; EI-Q: echo intensity of quadriceps; CSA-H: cross sectional area of hamstrings; EI-H: echo intensity of hamstrings; T60-Q: quadriceps torque at 60°/s; T300-Q: quadriceps torque at 300°/s; T60-H: hamstring torque at 60°/s; T300-H: hamstring torque at 300°/s.

The multicollinearity results demonstrated that none of the independent variables of the quadriceps (VIF ≤ 1.255) and hamstrings (VIF ≤ 1.153) were excluded from the backward multiple linear regression models. As shown in Table 3, 60.8% of maximal concentric knee extensor of DO at 60°/s can be explained together by positive relation with quadriceps CSA and negative relation with quadriceps EI [$F(2, 13) = 10.071$; $p = 0.002$], whereas 78.7% of maximal concentric knee extensor of DO limb at 300°/s can be explained together by positive relation with quadriceps CSA and negative relation with quadriceps EI [$F(2, 13) = 24.048$; $p < 0.001$]. Similarly, 61.0% of maximal concentric knee extensor of ND limb at 60°/s can be explained together by positive relation with quadriceps CSA and negative relation with quadriceps EI [$F(2, 13) = 10.148$; $p = 0.002$], whereas 74.9% of maximal concentric knee extensor of ND limb at 300°/s can be explained together by positive relation with quadriceps CSA and negative relation with quadriceps EI [$F(2, 13) = 19.374$; $p < 0.001$]; Figure 2.

Moreover, 75.2% of maximal concentric knee flexor of DO at 60°/s can be explained together by positive relation with hamstrings CSA and EI [$F(2, 13) = 19.684$; $p < 0.001$], whereas 70.4% of maximal concentric knee flexor of DO limb at 300°/s can be explained together by positive relation with hamstrings CSA and EI [$F(2, 13) = 15.493$; $p < 0.001$]. Likewise, 70.8% of maximal concentric knee flexor of ND limb at 60°/s can be explained together by positive relation with hamstrings CSA and EI [$F(2, 13) = 15.763$; $p < 0.001$], whereas 77.2% of maximal concentric knee flexor of ND limb at 300°/s can be explained together by positive relation with hamstrings CSA and EI [$F(2, 13) = 16.876$; $p < 0.001$]; Figure 3.

Table 3. Determinants of maximal voluntary concentric contraction at 60°/s and 300°/s of knee extensor and flexor. Independent variables are cross-sectional area (CSA) and echo intensity (EI) of quadriceps and hamstring, respectively.

Dependent Variable	r^2	ANOVA *p*-Value	Indicator	Standardized Coefficients (β)	Effect Size	Observed Power
DO-Q (60°/s)	0.608	=0.002	CSA and EI	0.744 and −0.072	1.55	0.98
DO-Q (300°/s)	0.787	<0.001	CSA and EI	0.862 and −0.054	3.69	1.00
ND-Q (60°/s)	0.610	=0.002	CSA and EI	0.519 and −0.403	1.56	0.98
ND-Q (300°/s)	0.749	<0.001	CSA and EI	0.665 and −0.338	2.98	1.00
DO-H (60°/s)	0.752	<0.001	CSA and EI	0.785 and 0.371	3.03	1.00
DO-H (300°/s)	0.704	<0.001	CSA and EI	0.732 and 0.413	2.38	1.00
ND-H (60°/s)	0.708	<0.001	CSA and EI	0.732 and 0.226	2.42	1.00
ND-H (300°/s)	0.772	<0.001	CSA and EI	0.709 and 0.276	3.50	1.00

DO-Q: quadriceps dominant; ND-Q: quadriceps non-dominant; DO-H: hamstrings dominant; ND-H: hamstrings non-dominant.

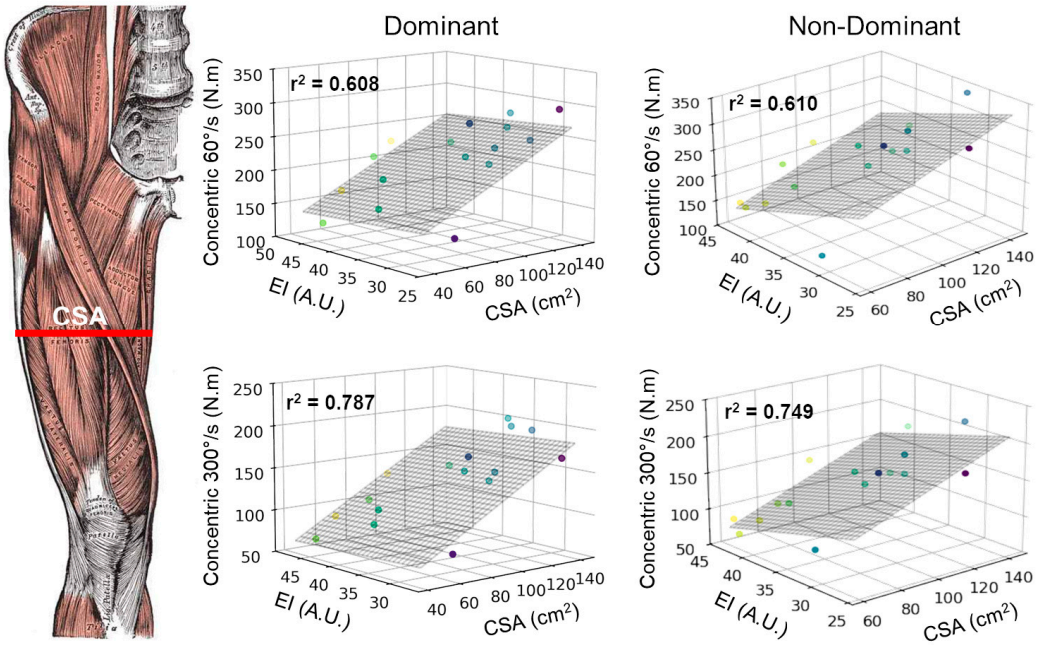

Figure 2. Three-dimensionally illustrated linear regression between independent variables (cross-sectional area—CSA; echo intensity—EI) of quadriceps with dependents variables (knee extensor maximal voluntary concentric contraction at 60 and 300°/s) in dominant and non-dominant limbs of team sports athletes.

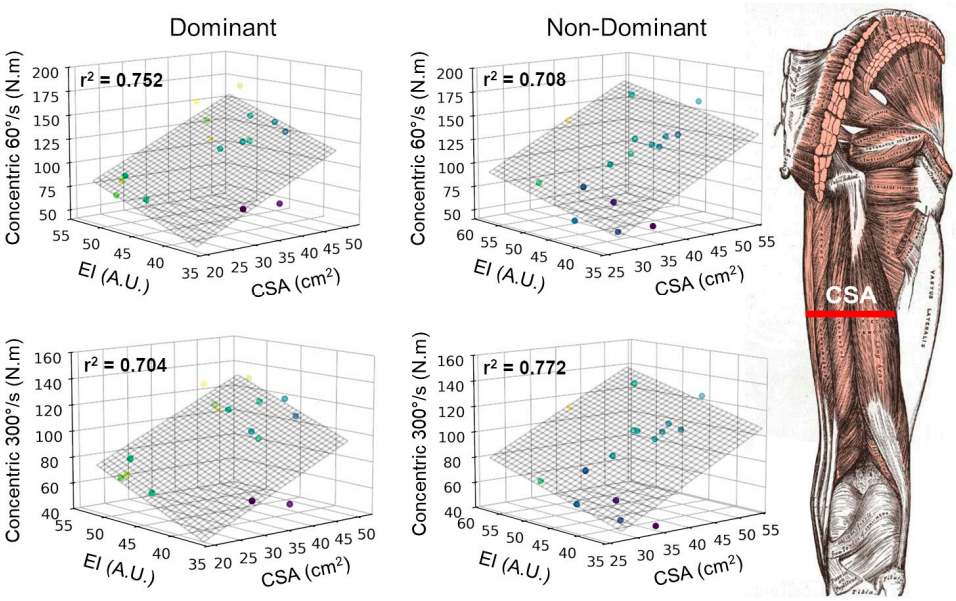

Figure 3. Three-dimensionally illustrated linear regression between independent variables (cross-sectional area—CSA; echo intensity—EI) of hamstrings with dependents variables (knee flexor maximal voluntary concentric contraction at 60 and 300°/s) in dominant and non-dominant limb of team sports athletes.

4. Discussion

The primary objective was to assess the morphological muscle symmetries (CSA and EI) and torque of quadriceps and hamstrings between the DO and ND limbs in competitive athletes practicing team sports. The secondary objective was to examine the relationship between the maximum concentric torque (60°/s and 300°/s) of quadriceps and hamstrings, based on CSA and EI, in the respective muscle groups. No significant differences were found between limbs for CSA, EI, or torque, indicating bilateral symmetries in quadriceps and hamstrings between the DO and ND sides. Additionally, CSA and EI of quadriceps and hamstrings were determinants of knee extensor and flexor maximal concentric torque at 60 and 300°/s.

Our findings on symmetry between DO and ND limbs and their muscle morphological characteristics (CSA and EI) corroborated the findings of Lanferdini et al. [41], reporting no differences between sides for the CSA and EI of the quadriceps in cyclists. Furthermore, Denadai et al. [42] also found no difference in quadriceps and hamstring CSA between DO and ND limbs in soccer players. Combining these findings suggests that the extent of morphological asymmetries may influence muscle strength, as the absence of torque asymmetries between sides appears to be associated with a lack of morphological differences.

The investigation of torque asymmetries has become a prominent topic in sports science, as it may impact in injury risk, performance and functional adaptation [5,43,44]. Regarding injury risk, limb strength asymmetry (equal or more than 15% of strength imbalance between sides) can lead to biomechanics alterations in sports movements, increasing the risk of injury [45]. Additionally, the muscle size characteristics (e.g., muscle volume or CSA) may have influence in strength as well as the extent of strength asymmetries. When strength asymmetry is identified, implementing a targeted strength training program is recommended to restore the balance in force production [46–50].

Our results also highlighted muscle quality by EI analysis as an important variable for understanding muscle force, reflecting the amount of contractile tissue in a given area [12]. Our results demonstrated that the assessment of EI can complement another small aspect of musculoskeletal performance alongside CSA. Corroborating our findings, Fukumoto

et al. [24] showed that muscle thickness and EI, as independent variables, significantly explained 29% of muscle strength. Additionally, they found a low negative correlation between EI and muscle force (r = −0.40), consistent with the findings of Cadore et al. [27], who reported low and moderate correlations of muscle EI with isometric and concentric knee extension torque (r = −0.48 to −0.67, respectively). However, the lack of evidence on the specific role of EI in each muscle remains a limitation, as this variable has been shown to be associated with performance-related tasks such as vertical jumps, sprints and agility [51]. Given these associations, incorporating EI in future studies could lead to more accurate prediction of muscle strength, as it provides insights into muscle quality that CSA alone may not capture.

Our findings demonstrated that CSA and EI from quadriceps and hamstrings are determinants of knee extension and flexion concentric torque, corroborating Kellis et al. [47], who also found quadriceps CSA explain 79% of maximum isometric knee extension torque in healthy subjects. However, the authors reported that hamstrings CSA only represents 25% of maximum isometric knee flexion torque in health subjects, a value lower than our findings (more than 70%). The discrepancies could be attributed to two points: (I) Our protocol was based on torque–velocity concentric contractions, whereas Kellis et al. [47] used isometric contractions of knee extension and flexion. (II) The isometric contraction of knee extension and flexion torque at 45° knee flexion used by Kellis et al. [47] may not represent the maximum force capacity of both muscle groups, as the muscle is not at its optimal length for maximum force production [52]. In contrast to our results, the authors related that the relation between quadriceps and hamstrings did not seem to be determinate by muscle groups CSA relation. This discrepancy might be explained by differences in the population studied, as only nine soccer professional players participated in their study, and they only collected five maximum voluntary contractions of the knee extensors and flexors at 60°/s to assess Hcon:Qcon [42].

These disagreements in the literature might stem from a misunderstanding of the contribution of each muscle within the CSA of the involved muscle groups, as each muscle plays a distinct role in force production and performance [19,47,53]. In line with this, Sekir et al. [19] demonstrated the correlations between quadriceps CSA (e.g., rectus femoris) and isometric and isokinetic strength; regression analysis showed that CSA of the rectus femoris measured during the relaxed knee at 60° of flexion (r^2 = 0.53–0.61) was a significant predictor of both isometric and concentric strength of knee extension. Similarly, Kellis et al. [47] found a substantial contribution of vastus medialis and long head of the biceps femoris CSA to maximum isometric voluntary contraction (r^2 = 0.72; r^2 = 0.27, respectively). Additionally, CSA of vastus medialis has been linked to performance in specific tasks, such as squat variations (r^2 = 0.50–0.57) [53].

When CSA, EI, and torque variables are analyzed together, opposite Q:H correlations emerge. These differences between the extensors and flexors of the knee may be attributed to the influence of the pennation angle of fascicles, which, when reduced, affects how the ultrasound wave is reflected, producing a clear image. However, the quadriceps muscles have a greater pennation angle when compared to the hamstrings, thus the transmission of force from each fascicle to the line of action of the force is impaired [32,54]. Additionally, EI can vary depending on the predominant muscle fiber type [55]. The opposite relation between EI and hamstrings compared to EI and quadriceps may be influenced by the greater amount of adipose, non-contractile tissue in flexor CSA [31].

Other measures of muscle size may provide a more comprehensive understanding of sports performance and injury prevention, for example, Hori et al. [56] demonstrated that quadriceps muscle volume and knee extensor joint moment arm are significantly correlated with knee extensor isometric torque (r = 0.78 and 0.79, respectively). Kulas et al. [9] aimed

to investigate the magnitude of volume asymmetries of the quadriceps and hamstrings muscles in healthy individuals and found volume asymmetries of the entire muscle group of quadriceps (8.8%) and hamstrings (11.4%) with a 95% limit of agreement.

The present data have some limitations, such as the small sample size. Despite this, the results of the backward multiple linear regression model demonstrate high power and effect size. However, we suggest that future studies carry out our experiments with a larger sample size, thus ensuring greater reliability of the statistical model used in this study. Furthermore, assessment of CSA in the same femur length does not represents the complete muscle size. Otherwise, this technique correlates with the golden standard, magnetic resonance [57]. Furthermore, the lack of evidence about each muscle in function and muscle strength may be necessary in future research to understand the true role of CSA and muscle quality in sports performance.

5. Conclusions

In summary, our results demonstrated bilateral symmetries between DO and ND lower limbs in CSA, EI, and torque of the quadriceps and hamstrings muscle groups in amateur team-sports athletes. Furthermore, quadriceps CSA and EI determined 61–79% of the maximal concentric knee extensor torque in both lower limbs at different angular velocities (60°/s and 300°/s). Similarly, hamstring CSA and EI explained 70–77% of the maximal concentric knee flexor torque of both lower limbs at the same angular velocities in these athletes.

Practical Application

Quadriceps and hamstring CSA and EI play a critical role in determining muscle groups' performance. Advanced imaging techniques provide valuable insights into muscle size and quality, enabling advanced strategies for controlling training load and athlete performance. Research highlights the links between CSA, EI, and performance, emphasizing the value of targeted hypertrophy and muscle quality training. Monitoring these changes helps assess training effectiveness and guide adjustments for better performance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15042102/s1, Table S1: All dataset.

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