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ORIGINAL RESEARCH

Quadriceps Muscle Geometry and Strength Throughout Maturation in National-Level Male Soccer Players: A Cross-Sectional Study

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Purpose: Adolescent soccer players experience distinct physiological changes due to chronological and biological maturation, impacting their soccer performance. Here, we explored age-related variations and associations between quadriceps geometry and strength in male national-level adolescent soccer players.

Patients and Methods: We used ultrasonography to examine the regional architecture and morphology of the rectus femoris (RF) and vastus lateralis (VL) muscles, and we assessed knee extension strength by isometric and isokinetic dynamometry. Players were categorized into four age groups: under (U) 15 (n=18, age=13.7±0.5 years), U16 (n=15, age=14.7±0.5), U17 (n=19, age=15.7±0.5), U18 (n=18, age=16.7±0.5) and U21 (n=25, age=18.5±0.5).

Results: The absolute and relative strengths were higher in the U16 compared to U15 by 12–15% and 6–8%, 11–12% and 6–7% in the U17 compared to U16, 5–7% and −1–2% in the U18 compared to U17 and 0–15% and −1–11% in the U21 compared to U18 age groups, respectively. VL architecture did not change relevantly between the age groups. The muscle anatomical cross-sectional area (ACSA) of the VL and RF differed non-uniformly and muscle region-specific by 10–36%, with highest values in the U21 age group. Moderate correlations between the VL architecture and knee extension strength in both legs were observed only in the U16 age group. The quadriceps ACSA showed age-specific correlations with knee extension strength.

Conclusion: Our findings highlight non-uniform differences in quadriceps muscle morphology and absolute and relative strength among male national-level adolescent soccer players in different age groups. The correlations observed between muscle morphology or architecture and strength were muscle, muscle region, leg and age dependent.

Keywords: strength, youth, muscle architecture, vastus lateralis, rectus femoris

Introduction

The m. quadriceps femoris plays a pivotal role in determining various performance metrics in soccer. Knee extension strength is linked to sprinting capabilities and vertical jump height among soccer players.[1–3] Furthermore, knee extension strength appears to correlate with foot velocity, influencing kicking performance.[4] Notably, diminished quadriceps strength in soccer players has been identified as a potential predisposing factor for injuries in this muscle group.[5] This is especially critical in youth soccer players, where the anterior thigh is one of the most frequently injured regions.[6,7]

Maturation introduces distinct physiological changes in adolescents that can manifest as different soccer-related performance outcomes. These effects are well known, with increases in sprint performance, explosiveness, aerobic fitness and strength.[8–11] Muscle function is partly governed by muscle geometry[12,13] as well as neural properties such as the

Received: 14 June 2024
Accepted: 14 June 2024
Published: 19 October 2024

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number of recruited motor units and their discharge rates.[14] Therefore, it is reasonable to assume that these parameters change throughout chronological maturation as well.

Indeed, accompanying increases in quadriceps strength, several investigations demonstrated changes in quadriceps architecture and morphology due to maturation in boys, girls and youth soccer players.[11,15–17] Due to their accessibility and functional relevance, most investigations have been conducted in the vastus lateralis or gastrocnemius medialis. One common finding of those studies was the continuous increase in muscle volume, muscle thickness or muscle anatomical cross-sectional area (ACSA), with changes of 5 to 20% from pre- to post-puberty.[10,11,15–18] However, reported results for changes in muscle fascicle length and pennation angle differ from studies reporting increases[10,16,17] or no effects[11] due to maturation, and data for regional muscle adaptation is not available.

Based on the changes in knee extension strength and quadriceps muscle geometry, it becomes pertinent to question whether their relationship also changes across different stages of maturation. Intriguingly, due to the non-uniformity in shape and geometry across a muscle's length,[19,20] this association might vary depending on the specific region assessed. In fact, recent findings in adults suggest that the relationship between the quadriceps ACSA and strength might depend upon the specific region of the thigh.[21,22] Considering the significance of knee extension strength in soccer performance,[1,2] gaining insight into the associated muscle geometry is valuable for training strategies.

Therefore, we assessed knee extension strength, the vastus lateralis (VL) and rectus femoris (RF) muscle ACSA, fascicle length and the pennation angle in youth national-level male soccer players in different age groups. Moreover, we aimed to describe the associations between knee extension strength and regional muscle geometry within each age group.

Materials and Methods

In this study, we used ultrasonography to assess knee extensors architecture and morphology and measured strength using a dynamometer during the soccer off-seasons in January and July 2021. All assessments were completed within a single day following a randomized sequence.

Our participants comprised a total of 96 male national league youth soccer players. The under 15 age group consisted of 18 players (aged: 13.7 ± standard deviation 0.5 years, height of 170.3 ± 8.6 cm, body mass of 57.8 ± 6.9 kg, and skeletal muscle mass of 29.6 ± 4.1 kg). The under 16 age group consisted of 15 players (aged 14.7 ± 0.5 years, height of 172.5 ± 5.9 cm, body mass of 61.7 ± 5.2 kg, skeletal muscle mass of 31.4 ± 3 kg). The under 17 age group consisted of 19 players (aged 15.7 ± 0.5 years, height of 177.5 ± 5.1 cm, body mass of 65.2 ± 6.2 kg, skeletal muscle mass of 33.1 ± 3.7 kg). The under 18 age group consisted of 18 players (aged 16.7 ± 0.5 years, height of 178.9 ± 4.9 cm, body mass of 68.9 ± 8.6 kg, skeletal muscle mass of 35.6 ± 4.2 kg). The under 21 age group consisted of 18 players (aged 18.5 ± 0.5 years, height of 178.8 ± 7.1 cm, body mass of 72.2 ± 8.4 kg, skeletal muscle mass of 37.4 ± 3.8 kg). These athletes played at the national level,[23] competing in Switzerland's top-tier junior league and adult 3rd highest league. The players trained between six and nine hours weekly with one additional soccer match per week. When determining leg dominance, we inquired about each athlete's preferred leg for kicking: 76% favoured their right leg. Our research adhered to the guidelines of the Declaration of Helsinki and received approval from the regional ethics committee (Ethics Committee of North-Western and Central Switzerland, approval number: 2017–02148). Parents of younger players or players older than 16 years provided written consent.

Assessment of Muscle Geometry and Strength

We investigated the morphology of the VL and RF muscles. We further examined the VL muscle architecture in both legs using B-mode ultrasonography (ACUSON Juniper, SIEMENS Healthineers, Erlangen, Germany) with a 5.6 cm linear probe (6.2–13.3 MHz, 12L3, Acuson 12L3). Participants were placed in a supine position with straight legs. We evaluated the VL and RF muscle ACSA, as well as the VL muscle thickness, fascicle length, and pennation angle at 33% (proximal), 50% (middle), and 66% (distal) of the femur length[20,24] The length of the femur was measured from the greater trochanter to the lateral condyle. We took at least two snapshots of the VL thickness, fascicle length, and pennation angle with the ultrasonography probe aligned perpendicularly to the skin, lining up in the fascicle direction (Figure 1). We also captured two panoramic images of the RF and VL ACSAs by moving the scanner across the muscles in the transverse plane (Figure 1),[20,25] ensuring minimal pressure was exerted on the skin.

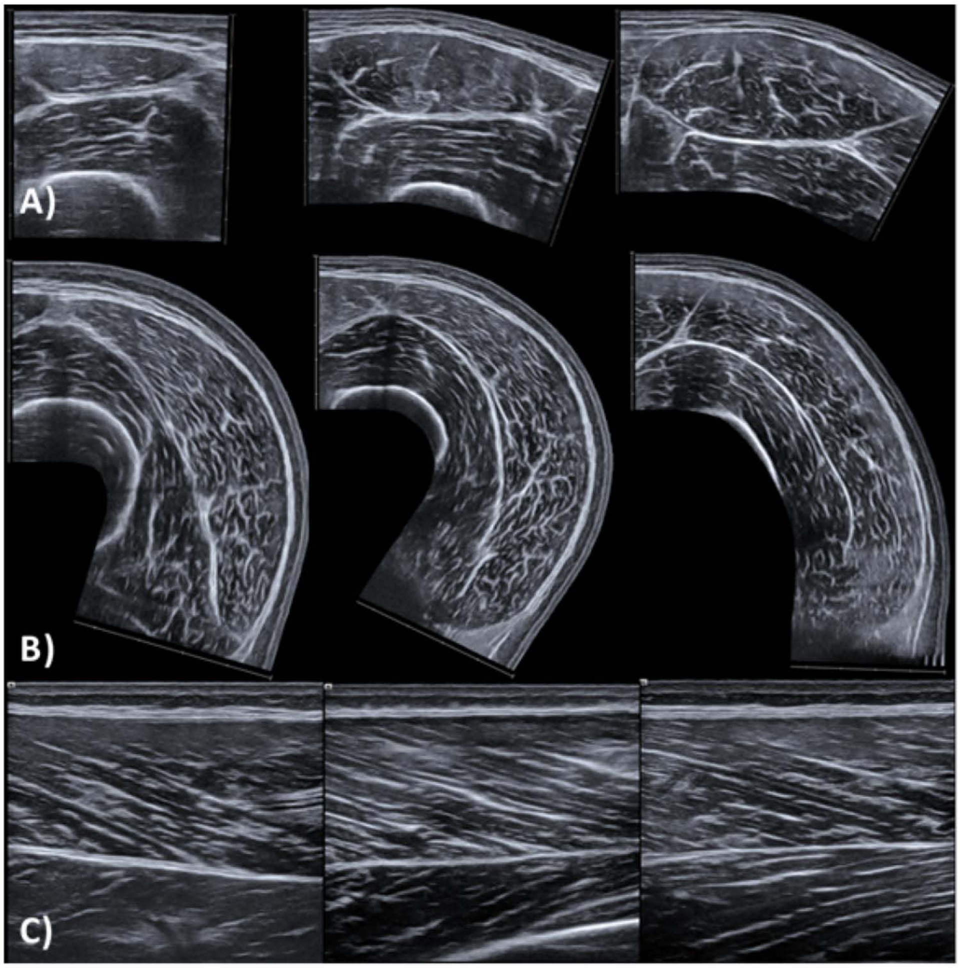

Figure 1 Ultrasonography images of one player at all scanned locations and planes. (**A**) rectus femoris anatomical cross-sectional area at 66%, 50% and 33% of femur length (from left to right). (**B**) vastus lateralis cross-sectional area at 66%, 50% and 33% of femur length. (**C**) vastus lateralis architecture at 66%, 50% and 33% of femur length.

For strength testing of the knee extensors, we employed an isokinetic dynamometer (IsoMed 2000, D&R Ferstl, Hemau, Germany) according to a validated methodology.[26] Players were instructed to give their maximum effort during tests. Prior to official measurements, warm-up exercises of varying intensities were conducted. Then, we assessed isometric and isokinetic strength. The isometric test comprised three attempts with a 20-second recovery period. Participants were instructed to perform isometric muscle actions as "fast" and as "hard" as possible and hold them for up to 5 seconds.[27] The isokinetic test involved two sets of five repetitions, with 45 seconds of recovery. While seated, participants had their hip at 75° and their knee at 60° (with 0° being full extension) for the isometric test. The isokinetic test was limited between 15 and 90° at speeds of 60°/s and 240°/s. Securement was provided at the shoulders and waist, with the machine aligned with the knee's pivot point and the dynamometer arm fixated at one-third of the distance between the lateral malleolus and the fibular head.

Muscle architecture images were processed using DL_Track_US,[28,29] and panoramic ACSA snapshots were analysed using DeepACSA.[30] If the automated outputs seemed visually flawed, ACSAuto[31] was employed for the ACSA snapshots, and manual analysis was employed for the architecture images. As two to three images were taken per area for each participant, the averaged results were used for subsequent computations.

Force data during knee extension were collected at a frequency of 200 hz and processed in Excel (Microsoft, Redmond, USA). We utilized a 2nd-order Butterworth filter to refine the torque readings, setting a 1.5 hz threshold. The peak torque measurements were derived for all test types. The maximum torque achieved across the three isometric trials was selected for additional computations. For the isokinetic tests, we analysed the second through fifth repetitions in each trial. The peak torque from the two isokinetic tests was chosen for deeper scrutiny. In addition to the absolute torque measures from both the isometric and isokinetic tests, we also derived torque values relative to the participant's body mass.

Using the assessed anthropometric variables we calculated the maturity ratio and age at peak height velocity based on the equation presented by Fransen et al.[32] The formula includes chronological age, stature, body mass, and leg length. The maturity is a somatic biological maturity indicator reflecting the age of an adolescent at which maximum growth occurs.[33]

Statistical Analyses

All analysis tasks were executed using R[34] and Excel. We checked the normality of the distribution with the NormalityAssessment tool in R.[35] Mean values, standard deviations, and age-related differences (with 95% compatibility intervals, alpha level = 0.05) were computed. We calculated the associations between muscle characteristics and strength parameters using partial correlations corrected for body mass, height and the maturity ratio. We used Spearman's ρ to describe the correlations due to non-linearity and non-normality of the data. We established the correlation benchmarks per Schober et al[36] as weak ($\rho<0.4$), moderate ($0.4<\rho<0.7$), and high ($\rho\geq0.7$). The statistical analysis script can be found in Supplementary Material A.

Results

Differences in Quadriceps Muscle Architecture, Morphology and Strength

The mean trajectories of all assessed strength and muscle architectural as well as morphological parameters comparing the five included age groups are displayed in Figures 2 and 3. Furthermore, the mean differences, standard deviations, percentage mean differences and standardized mean differences with 95% compatibility intervals for all assessed strengths and muscles are included in Supplementary Material B. The absolute strength differed between 11 and 15% per year until the U17 age group and 3 to 13% between the U17, U18 and U21 age groups. The relative strength differed by 6 to 8% per year, again displaying a lower difference between the U17 and U21 age groups (1 to 2%), with only the relative strength at high knee angle velocities markedly differing by 10% from the U18 to the U21 age groups. In general, the vastus lateralis fascicle length, pennation angle and muscle thickness did not differ among the age groups in either leg, except in the distal muscle region (Figures 2 and 3). However, the muscle ACSA of the VL and RF differed by 9 to 36% in all assessed muscle regions from the U15 to the U21 age groups in both legs, with the highest values observed in the U21 group. The regional VL ACSA differed between −6 and 19% comparing the U15 and U16 age groups, but demonstrated smaller differences between the U16 and U17 age groups (−4 to 15%). The regional VL ACSA differed from 4 to 12% and 2 to 12% between the U17 and U18 and between the U18 and U21 age groups, respectively. The RF ACSA differed from −26 to 7% between the U15 and U16 age groups, with large decreases observed in the distal muscle region. Between the U16 and U17 age groups, the RF ACSA differed by 7 to 34% but seemed to decrease slightly between the U17 and U18 age groups, with differences of −16 to 5%. The RF ACSA further differed between the U18 and U21 age groups (2 to 17%), with predominant differences in the left leg (14 to 17%). The muscle ACSA adaptations were not uniformly distributed throughout the muscle. Both the VL and RF ACSA, seemed to increase predominantly (and constantly) in the proximal regions of the muscles (Figures 2 and 3).

Relationships Among Quadriceps Muscle Architecture, Morphology, and Strength

Muscle Architecture

We did not observe a consistent and relevant linear relationship for VL fascicle length, pennation angle or muscle thickness with isometric or isokinetic knee extension strength across all age groups when corrected for body mass, height or maturity ratio (Figures 4–6). Nevertheless, it seemed that the VL fascicle length in the middle muscle region was moderately and strongly correlated with isometric and isokinetic (60°/s) knee extension (r = 0.50–0.89, see Supplementary Material C) in the U16 age group. Notably, these data are also compatible with weak to strong correlations. Accordingly, the VL pennation angle in the middle muscle region was moderately negatively correlated

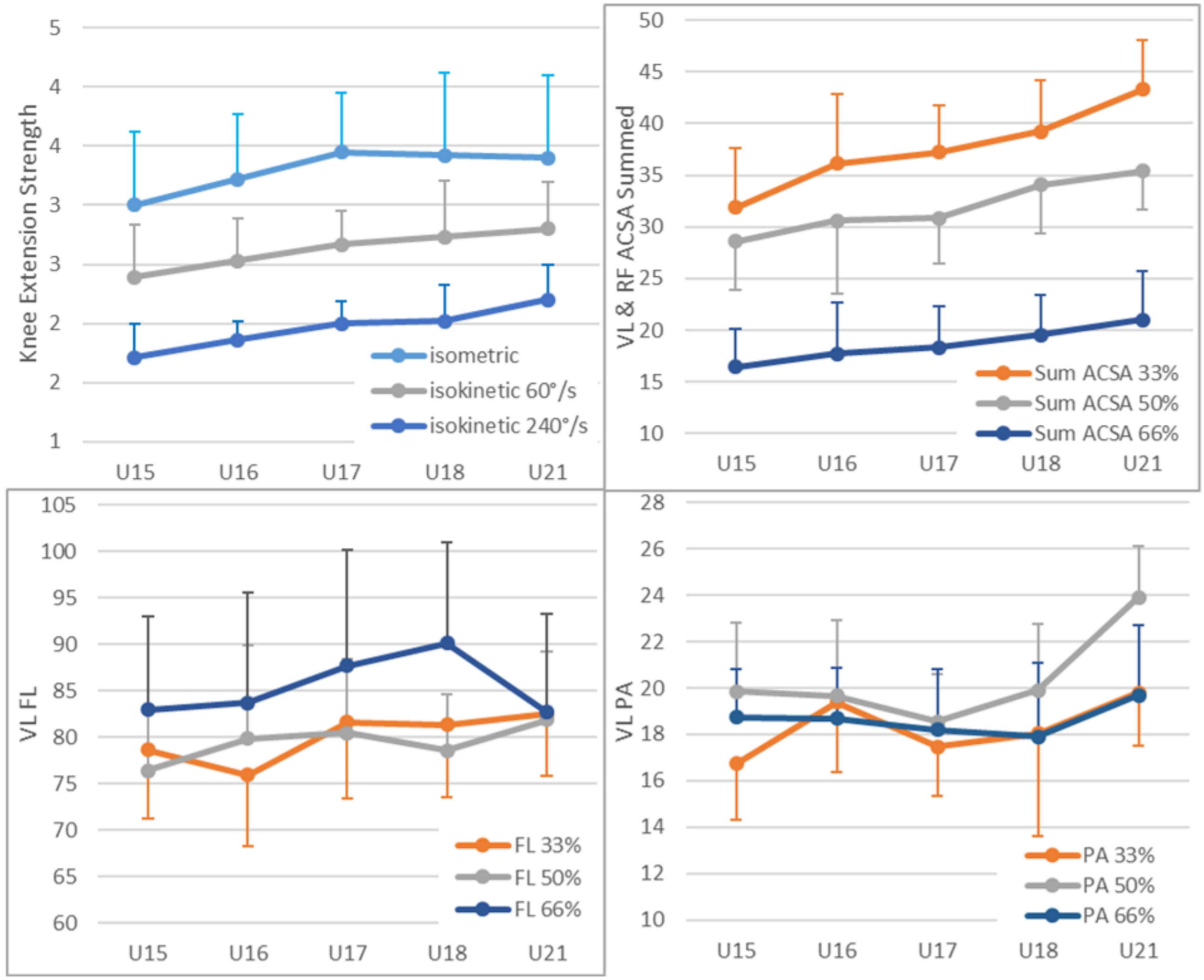

Figure 2 Mean trajectories for assessed strength (relative to body mass) and muscle architectural and morphological parameters of the right leg in different age groups with standard deviations indicated as bars. VL = vastus lateralis, PA = pennation angle (°), 66% = 66% of femur length (distal), 50% = 50% of femur length, 33% = 33% of femur length (proximal), FL = fascicle length (mm), acsa = anatomical cross-sectional area (cm²), rf = rectus femoris, sum = sum of vastus lateralis and rectus femoris.

with isokinetic (60°/s) knee extension in the U16 age group (Supplementary Material C). However, these data are also compatible with weak to strong correlations. When considering leg preference, we found no relevant difference in the strength of correlation coefficients compared to right- or left-side-specific analyses (Supplementary Material C).

Muscle Morphology

We did not observe a consistent or relevant linear relationship for VL the isometric or isokinetic knee extension strength and RF ACSA across all age groups when corrected for body mass and height (Figures 4–6). Moderate correlations were more frequent at isokinetic contractions with higher angular velocities and were most frequent in the U17 and U18 age groups (Figures 4–6). The VL ACSA, RF ACSA and sum of the VL and RF ACSA in the middle muscle region was moderately correlated to all tested strength conditions (r = 0.41 to 0.65) for the U18 age group (Figures 4–6). These data are also compatible with a weak to strong relationship. However, moderate negative correlations for RF ACSA and the sum of RF and VL ACSA with isokinetic strength at 240°/s occurred at different muscle regions in the left leg of U15 players (Figures 4–6), with the data being compatible with small to large correlations as well. When considering leg preference, we found no relevant difference in the strength of correlation coefficients compared to right- or left-side-specific analyses (Supplementary Material C).

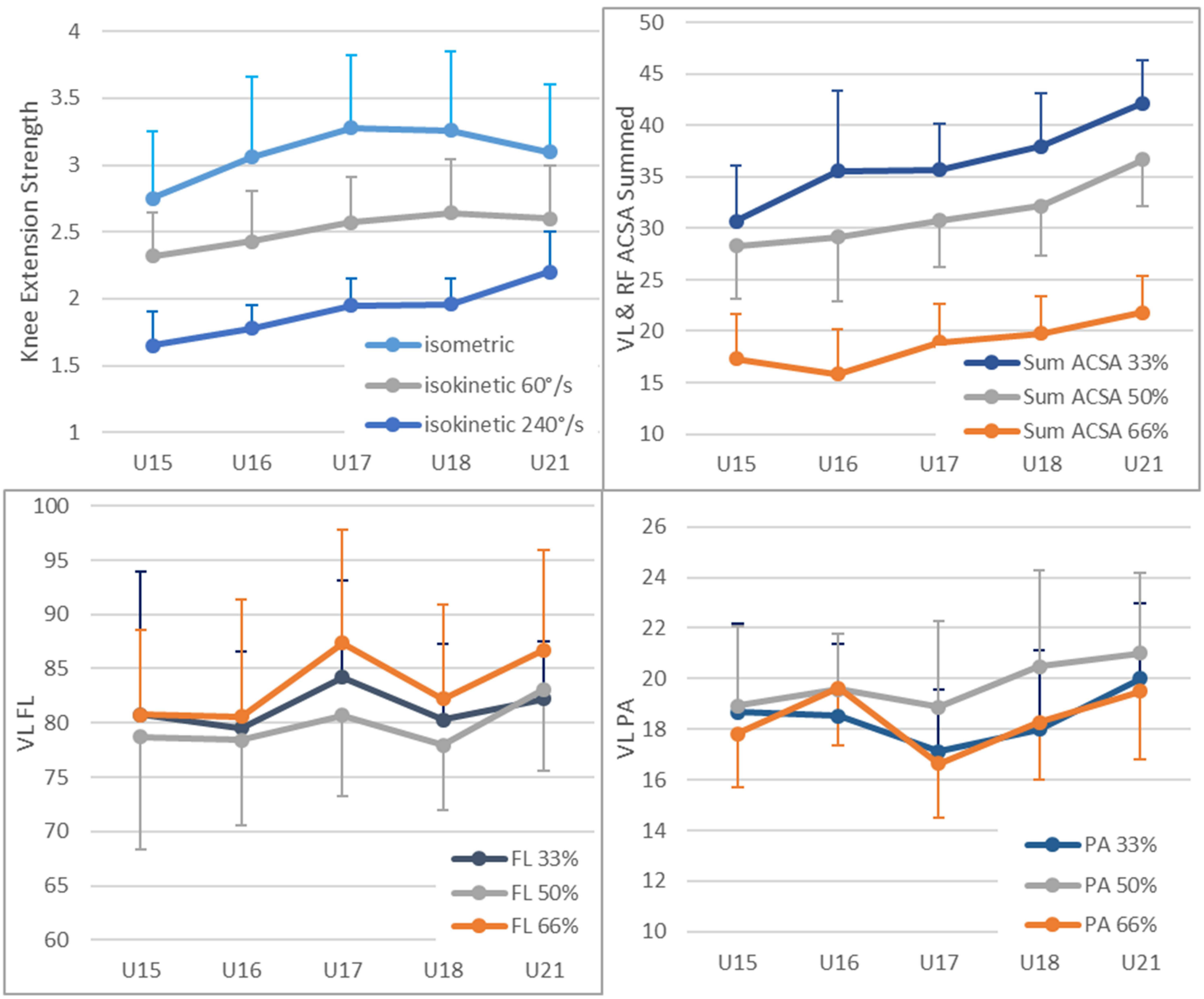

Figure 3 Mean trajectories for assessed strength (relative to body mass) and muscle architectural and morphological parameters of the left leg in different age groups with standard deviations indicated as bars. VL = vastus lateralis, PA = pennation angle (°), 66% = 66% of femur length (distal), 50% = 50% of femur length, 33% = 33% of femur length (proximal), FL = fascicle length (mm), acsa = anatomical cross-sectional area (cm²), rf = rectus femoris, sum = sum of vastus lateralis and rectus femoris.

Discussion

In this study, we investigated the differences in the muscle architecture, morphology and strength of the quadriceps muscles of youth national-level soccer players aged 14 to 21 years. Additionally, we investigated relationships between quadriceps strength and muscle architecture and morphology. Throughout the assessed age groups, the muscle ACSA of the VL and RF differed up to 36% from the under 15 to under 21 age groups, predominantly in the proximal muscle regions. Similarly, the absolute and relative isometric and isokinetic knee extension strengths differed by up to 49% from the U15 to the U21 the age groups. We observed no relevant differences between age groups in pennation angle or fascicle length. For the ACSA, stronger and more frequent correlations with strength were observed in the U17 and U18 age groups, specifically at 50 and 66% of femur length, respectively. Muscle architecture correlated with strength most frequently and strongly in the U16 age group, with only isolated moderate correlations in the other age groups and thus these relations should be interpreted with caution (see Supplementary Material C). However, all the observed relationships with muscle architecture and ACSA differed between age groups, legs, muscles and muscle regions.

Our findings on knee extensor torque in youth soccer players are in line with the literature,[37,38] with lower observed torque values at an angular velocity of 240°/s.[11] The increased differences in absolute knee extension strength with increasing age is to be expected in this population. However, we observed a relevant increase in torque relative to body

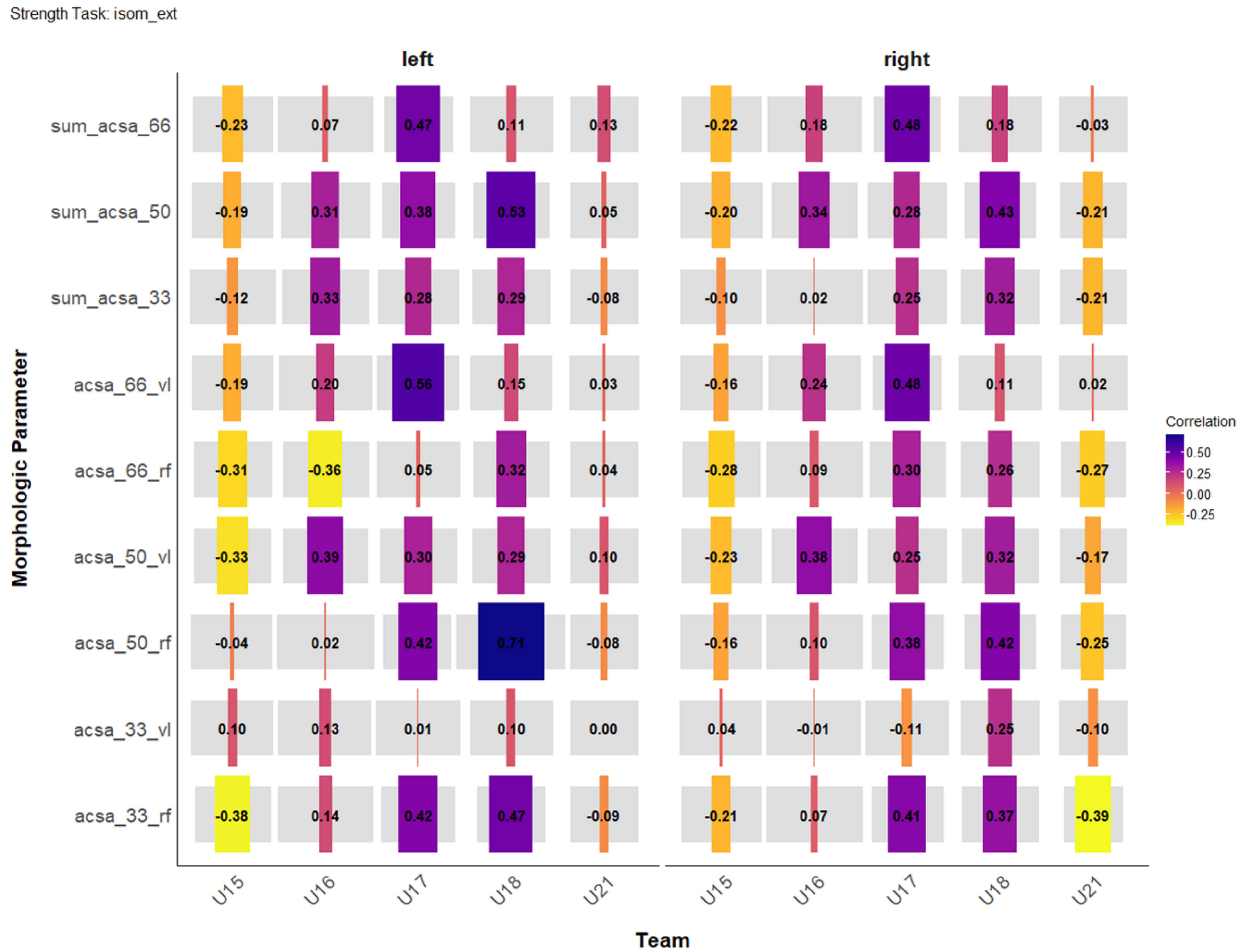

Figure 4 Age-specific correlations for muscle morphology of the right and left leg in cm² with assessed isometric absolute strength in Nm adjusted for height, body mass and maturity ratio. 95% compatibility intervals are displayed as shaded grey, whereas the width of the coloured square equals the size of the correlation coefficient. sum = sum of vastus lateralis and rectus femoris. acsa = anatomical cross-sectional area, 66 = 66% of femur length (distal), 50 = 50% of femur length, 33 = 33% of femur length (proximal), rf = rectus femoris, vl = vastus lateralis.

mass only from the U15 to the U17 age groups. This might be explained by the maturational development of neural structures up to the age of around 16 years,[8] especially since we observed muscle ACSA to be highly correlated with body mass. For example, a recent review described that antagonist co-activation decreases and motor unit recruitment seems to improve until the age of 15–16 years, with comparable values to those of adults afterwards.[8]

Because most neuromuscular properties seem to be similar between post pubertal adolescents and adults,[8] adaptation caused by a greater training load, hormonal differences and hypertrophy might explain the observed strength differences.[39–41] Furthermore, our results support the assumption that muscle architecture does not change relevantly between adolescents (>14 years of age) and adults (>21 years of age) of similar populations based on similar VL architecture values throughout all observed age groups.[8]

Our values for muscle geometry are in agreement with recent investigations, although geometric calculations of muscle fascicle length were used in some studies.[10,11,16,42] However, no comparable data for the VL ACSA in this population are available. At the national youth level, the muscle architecture of male soccer players does not differ among the age groups. Nonetheless, our results demonstrate weak to moderate associations between the assessed knee extension strength and the VL architectural parameters and maturity ratio. However, consistent results are only present in the U16 age group (see Supplementary Material C). Therefore, given the generally observed weak to moderate and inconsistent associations of VL muscle architecture assessed statically and performance metrics throughout maturation,

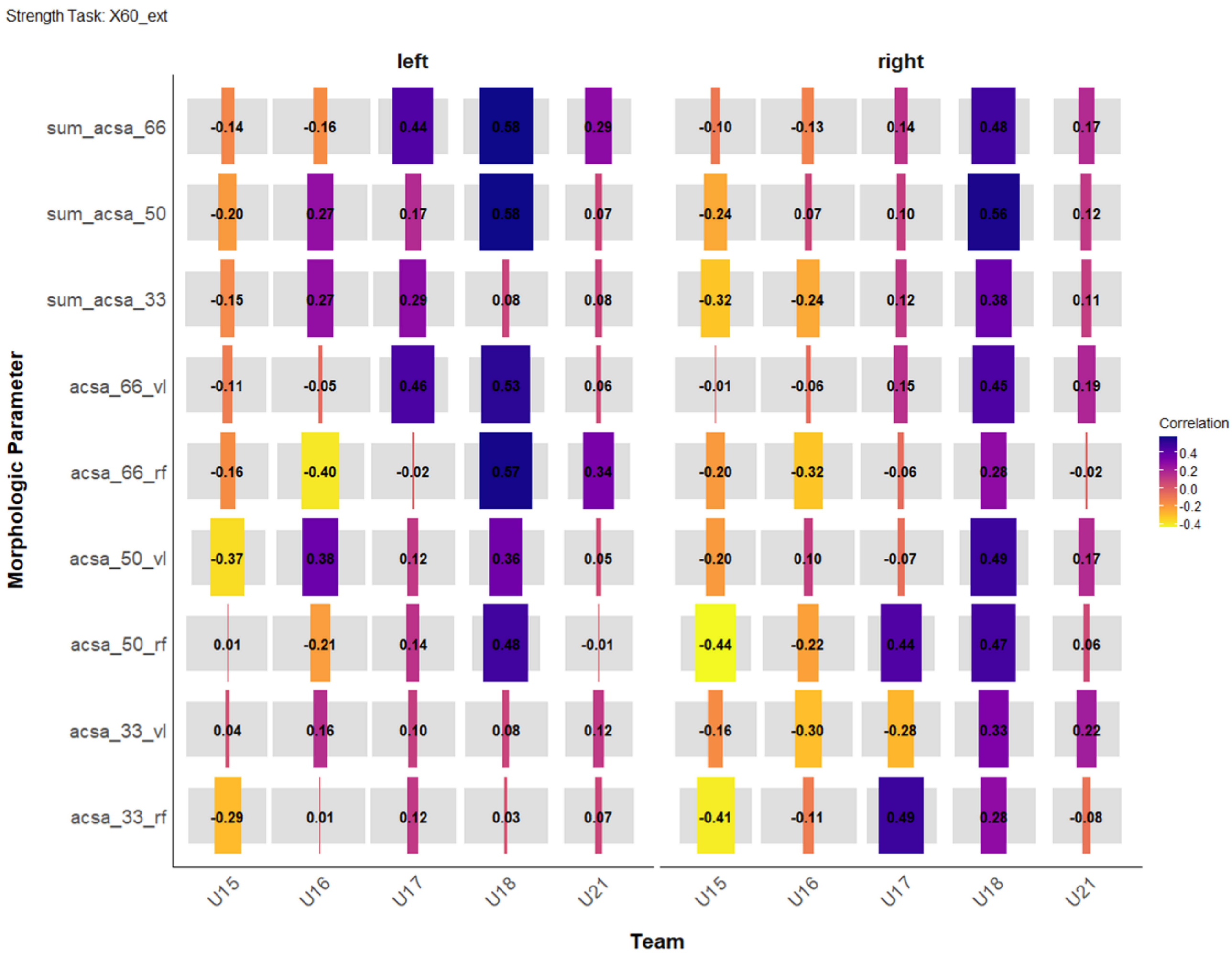

Figure 5 Age-specific correlations for muscle morphology of the right and left leg in cm² with assessed isokinetic absolute strength at 60°/s in Nm adjusted for height, body mass and maturity ratio. 95% compatibility intervals are displayed as shaded grey, whereas the width of the coloured square equals the size of the correlation coefficient. sum = sum of vastus lateralis and rectus femoris. acsa = anatomical cross-sectional area, 66 = 66% of femur length (distal), 50 = 50% of femur length, 33 = 33% of femur length (proximal), rf = rectus femoris, vl = vastus lateralis.

these results should be interpreted with caution. As indicated recently, muscle architecture assessed during the respective dynamic tasks might be more meaningful.[43,44]

Although the relationship between muscle mass and strength of the upper and lower limbs has been established in children,[11,15,45] we are unaware of any investigations determining the regional associations of knee extensor muscle size and strength. Whereas most investigations demonstrate relevant correlations throughout the maturation process, our results indicate more frequent and pronounced correlations in older adolescents. Given the non-linear development of the neuromuscular system, neuronal factors such as lower mechanical delay, tendon stiffness and reduced motor unit recruitment might mitigate the importance of knee extensor size for strength at a younger age.[8,46] However, our results are somewhat different from those of Fukunaga et al,[15] who reported a similar muscle strength-size relationship throughout puberty in 12- to 15-year-old boys. These authors used regression analysis to investigate the relationship between estimated muscle volume and knee extension strength in prepubescent and pubescent boys adjusted for chronological age. The disparate results might be explained by the different ages of the included populations as well as the number of investigated age groups.

In contrast to our general expectation, we observed moderate negative correlations between the ACSAs of the VL and RF muscles and strength for the U15 age group, predominantly in the left leg. This seems counterintuitive and might be due to the regional confinement of the information captured with the ultrasonography images. Although ultrasonography

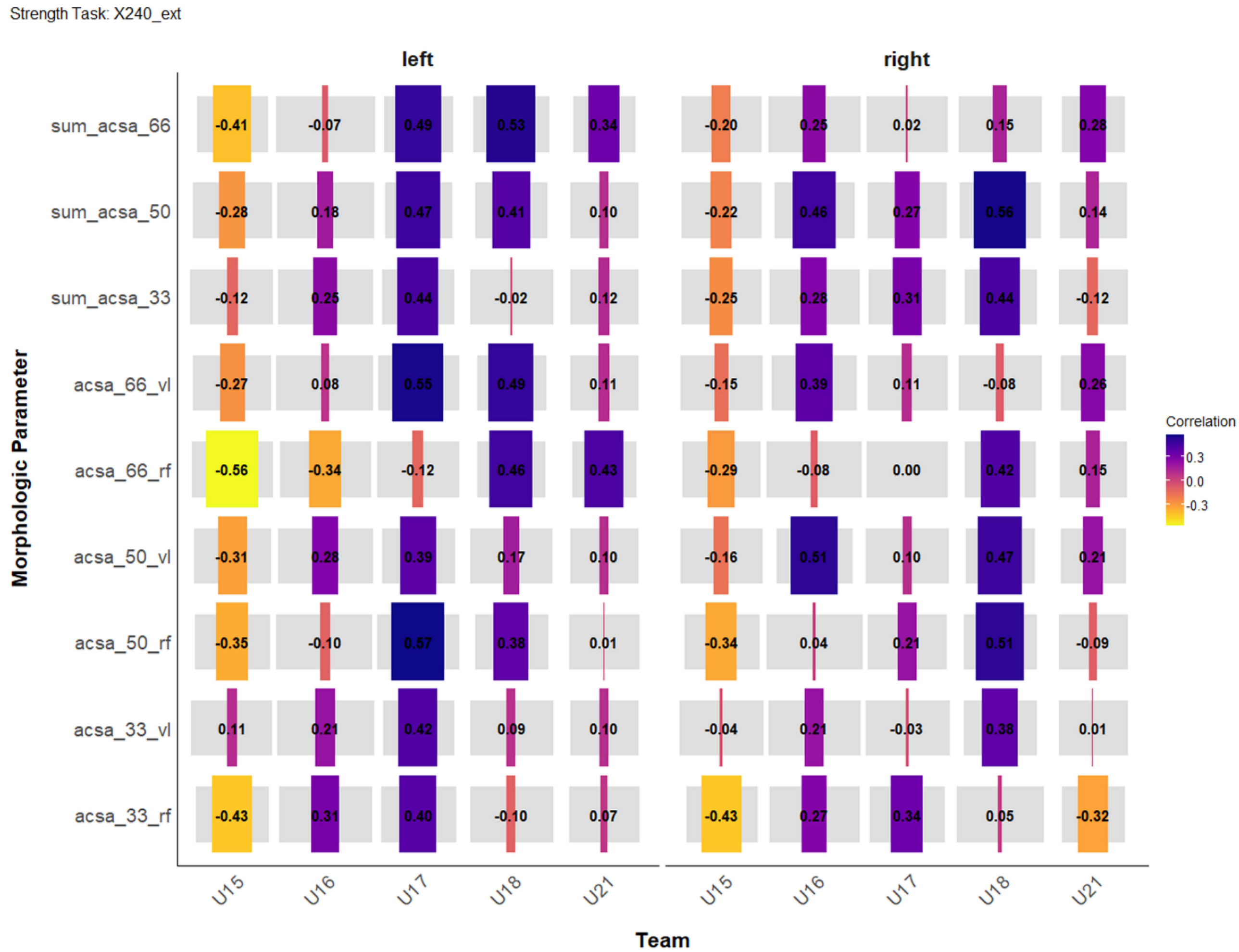

Figure 6 Age-specific correlations for muscle morphology of the right and left leg in cm² with isokinetic absolute strength at 240°/s in Nm adjusted for height, body mass and maturity ratio. 95% compatibility intervals are displayed as shaded grey, whereas the width of the coloured square equals the size of the correlation coefficient. sum = sum of vastus lateralis and rectus femoris. acsa = anatomical cross-sectional area, 66 = 66% of femur length (distal), 50 = 50% of femur length, 33 = 33% of femur length (proximal), rf = rectus femoris, vl = vastus lateralis.

allows for the investigation of regional muscle properties, the representativeness of the respective region for whole muscle volume is not equal.[47] Therefore, inconsistent results should be interpreted with care, and pooling the data from several muscles might be more robust.

A moderate correlation consistent across both legs occurred predominantly in the U18 age group between knee extension strength and muscle ACSA at 50% and 66% of femur length. Moreover, when summing the RF and VL ACSA, this moderate correlation was consistent across all strength measurement conditions in the U18 age group. There is no consensus in the literature as to which quadriceps muscle region is the most relevant for knee extension strength, as this might be dependent on the investigated conditions as well as hip and knee angles.[21,22,48]

This study presents several noteworthy limitations. First, we evaluated only two of the four quadriceps heads. Given their distinct morphological and architectural traits,[49] conclusions about the correlation of the remaining quadriceps heads with knee extension strength are not feasible. Nonetheless, based on their large combined volume, the VL and RF muscles are major contributors to knee extension strength.[50] Second, ultrasonography measurements were conducted at rest while participants were in a supine position. More recent studies have suggested that measurements taken during dynamic tasks or nearer to the optimal knee extension angle may be more relevant to performance.[43,44] Third, we did not adjust the knee extension torque for individual co-activation of antagonist muscles, possibly leading to an under-estimation of the true moment.[51] Fourth, our use of two-dimensional B-mode ultrasonography means we cannot factor in the three-dimensional muscle fascicle curvature.[25,52] The fifth point to consider is that the study's cross-sectional design prohibits any causality conclusions regarding the examined correlations. Sixth, we did not control for the strength training content of the players' strength training sessions performed during the soccer season or during the season break. Finally, our findings are specifically applicable to national-level adolescent male soccer players.

Conclusion

To conclude, this investigation provides insights into the associations among quadriceps muscle architecture, morphology, and strength in national-level adolescent male soccer players. The observed associations were age-, muscle- and muscle region-dependent and indicated that the quadriceps muscle ACSA at 50% of the femur length might be most strongly related to the maximum voluntary knee extension strength. Nonetheless, we found no consistent relevant relationship between muscle architecture and strength, except for the U16 age group, which should be interpreted with caution. These insights can guide practitioners in tailoring training protocols for national-level male adolescent soccer players.

Abbreviations

ACSA, Muscle anatomical cross-sectional area, RF, rectus femoris, VL, vastus lateralis, U, under.

Data Sharing Statement

The analysis scripts used in this study are openly available in Supplementary Material A. The data will be made available in anonymized form upon reasonable request.

Acknowledgments

We would like to thank the players as well as the coaches of the FC Basel 1893 for taking part in this investigation.

Funding

This work was not supported by any specific funding.

Disclosure

The authors report no conflicts of interest in this work.

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