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Handgrip Strength and Isokinetic Knee Extensor and Flexor Torque in Adolescent Soccer Players

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Abstract

Handgrip strength (HGS) is often used as a quick index of general muscular strength, but it is unclear how well it reflects knee extensor and flexor strength in adolescent soccer players. In this cross-sectional study, 111 players aged 15–18 years completed bilateral HGS testing and concentric quadriceps and hamstring peak torque testing at 60°·s^{-1} during preseason. Because the sample was unbalanced by sex (81 male, 30 female), pooled, sex-adjusted, and sex-specific associations were examined for absolute and body-mass-normalized values. Pooled correlations of HGS with quadriceps and hamstring torque (r = 0.86 and 0.74) decreased to 0.68 and 0.42 after adjustment for sex, and to 0.63 and 0.36 in male players. The quadriceps association was significantly stronger than the hamstring association in the full sample and in each sex ($p < 0.005$), although the female estimates were imprecise. After age, sex, height, and body mass were entered in the model, HGS explained an additional 5.0% of the variance in absolute quadriceps torque ($p < 0.001$) and 0.7% in hamstring torque ($p = 0.084$), and in the pooled sample these covariates on their own explained more variance than HGS, mainly because of sex. Within each sex, HGS added 11.7% (male players) and 25.9% (female players) to the explained variance in quadriceps torque. The residual errors of the full models (15.6 and 17.3 Nm) indicate limited precision for estimating the knee strength of an individual player. HGS was more closely related to quadriceps than hamstring strength and may complement general strength profiling, but it should not replace joint-specific knee testing.

Keywords: adolescent; hand strength; muscle strength; muscle strength dynamometer; soccer; torque

Received: 7 October 2026
Revised: 15 November 2026
Accepted: 17 November 2026
Published: 19 November 2026

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1. Introduction

Muscular strength develops rapidly during adolescence and is an important component of physical performance in youth soccer [1]. Its assessment during this period is complicated by growth, biological maturation, body size, and training exposure, all of which influence strength and the interpretation of a single test result. For joint-specific assessment of the knee extensors and flexors, isokinetic dynamometry is commonly used because angular velocity and range of motion can be controlled under standardized conditions [2–4]. Handgrip strength (HGS) provides a much simpler alternative for general strength assessment. It is inexpensive, quick to administer, and easy to repeat in either

field or laboratory settings, which has contributed to its widespread use in athlete testing. Its value, however, depends on what the measure is intended to represent [5]. Although HGS is practical as a general strength measure, it remains uncertain how well it reflects knee extensor and flexor strength.

HGS is reliable in children and adolescents and is included among recommended field measures of musculoskeletal fitness [6,7]. Wind et al. [8] reported a strong relationship between HGS and a composite measure of strength from other muscle groups in children, adolescents, and young adults, although body mass explained part of this relationship. In youth soccer, Schulz et al. [9] examined 221 elite male players aged 11–18 years and reported correlations of 0.69–0.75 between HGS and jump performance and −0.62 to −0.73 with sprint times, with age and maturation moderating these associations. Some association between grip strength and lower-limb strength is expected on physiological grounds, because strength in different muscle groups depends partly on shared factors such as body size, overall muscle mass, and maturity status [8,9]. Grip strength, however, is produced isometrically by the forearm and hand, whereas knee torque reflects the dynamic capacity of the thigh muscles. HGS may therefore act as a broad marker of physical development, but whether it is meaningfully associated with objectively measured, joint-specific knee strength remains unclear.

Sprinting and jumping involve coordination, technique, stretch-shortening cycle function, and the contribution of several muscle groups. Isokinetic knee testing, in contrast, assesses knee extensor and flexor torque at a fixed angular velocity. Direct evidence relating HGS to isokinetic knee torque is limited and comes mainly from adults. Ostolin et al. [10] studied 780 asymptomatic adults and reported correlations of 0.71 between HGS and knee extension torque and 0.69 between HGS and knee flexion torque at 60°·s^{-1}. In the same cohort, however, one-year changes in HGS explained only a small additional proportion of the variance in changes in knee isokinetic function ($\Delta R^2 \approx 0.07$–0.12), leading the authors to conclude that muscle-specific testing remained necessary. Whether the same pattern is present in adolescent soccer players is unknown. In this population, both HGS and knee torque vary with age, maturation, and body size [2,3,9], while soccer training places substantially greater demands on the knee extensors and flexors than on the forearm muscles.

Body size is an important consideration when comparing two measures of strength. Larger players generally produce greater absolute force and torque, which can strengthen the apparent relationship between tests even when they assess different muscle groups. Associations based only on absolute values may therefore overestimate the extent to which HGS and knee torque reflect the same underlying characteristic. Examining values relative to body mass, together with models that account for age, sex, height, and body mass, provides a more accurate assessment of their relationship.

To our knowledge, HGS has not been directly compared with isokinetic knee torque in adolescent soccer players. This is relevant in practice because many youth soccer settings have limited access to isokinetic equipment, making it useful to establish whether a simple grip test provides meaningful information about knee strength and whether this differs between muscle groups. We therefore examined the associations between bilateral HGS and concentric isokinetic quadriceps and hamstring peak torque at 60°·s^{-1} in adolescent male and female soccer players. Both absolute and body-mass-normalized values were analyzed. We also tested whether age or sex modified these associations and quantified the additional variance in knee torque explained by HGS after accounting for age, sex, height, and body mass. We hypothesized that HGS would be positively associated with both quadriceps and hamstring torque and that both associations would weaken after normalization and covariate adjustment. The comparison between the quadriceps and

hamstring associations was not planned before the analyses, so it was treated as an exploratory question.

2. Materials and Methods

2.1. Study Design and Participants

This observational cross-sectional study used data from preseason laboratory testing during the 2023–2024 season and is reported in accordance with the STROBE guidelines [11]. A convenience sample of competitive adolescent soccer players who attended preseason laboratory testing with their clubs was used. In total, five teams took part. The 81 male players were from the academy teams of two first-division clubs, and the 30 female players played for three teams in the national under-18 championship. Male players who had an injury or a medical condition at the time of testing were not tested, and all 81 male players who were tested had complete data. Eleven male players had been entered twice in the database, and only their first entry was kept. Of the 42 female players who completed the assessments, 12 had been excluded in our previous study [12]. Two did not complete the preseason preparation, two changed teams, six had limited playing time in the friendly games, and two sustained a contact injury during the preseason. The present analysis therefore included the same 30 female players. The final sample consisted of 111 players aged 15–18 years (81 male and 30 female) who had complete anthropometric, bilateral HGS, and bilateral isokinetic knee data. Male players were 15–18 years old and female players 15–17 years old. All were registered with a soccer club and took part in regular organized training at the time of testing. The female players were also included in a previous study of knee mechanics, strength, and flexibility [12]. The present analysis addresses a different research question and adds the HGS data and the male players, neither of which was reported in that study.

A priori sample size calculation was not performed, because the sample size was set by the number of players available from the participating teams. Instead, we ran a sensitivity analysis with the Fisher z approximation (two-tailed $\alpha = 0.0125$, the Bonferroni-adjusted level used for the correlations; power = 0.80). With the full sample, correlations of $r \geq 0.31$ could be detected; the corresponding thresholds were $r \geq 0.36$ for male players and $r \geq 0.57$ for female players. The female subgroup was therefore underpowered for weak-to-moderate correlations. These thresholds describe the precision attainable for the correlation estimates only. They do not indicate adequate power for the interaction tests, because detecting differences in slopes between subgroups requires considerably larger samples.

Players aged 18 years gave written informed consent. For younger players, written consent was obtained from a parent or legal guardian, and the players agreed to take part. The data were collected as part of the routine annual preseason testing of the participating teams, and the signed consent forms included permission to use these data for research. The study followed the Declaration of Helsinki. The Cyprus National Bioethics Committee confirmed (reference EEBK EP 2024.13.12) on 13 December 2024 that these data could be published without a full proposal for bioethical review, because informed consent had been obtained, the data were collected as part of routine annual testing, the information could not be linked to any individual, and no sensitive personal or medical data were collected. The earlier study that included the female players was approved by the same committee (EEBK EP 2022.01.290, 29 January 2022) [12].

2.2. Anthropometry

Standing height (cm) and body mass (kg) were measured before the strength tests, and body mass index (BMI) was calculated as body mass divided by height squared

($kg \cdot m^{-2}$). Body mass was also used to express HGS and knee torque relative to body size. Chronological age was recorded in completed years at the time of testing and was entered in the regression models as a continuous variable, so decimal age was not available. Biological maturity status was not assessed. Male and female players went through exactly the same anthropometric and strength-testing procedures.

2.3. Handgrip Strength

Maximal isometric HGS was measured with an adjustable Takei handgrip dynamometer (Takei Scientific Instruments Co., Ltd., Tokyo, Japan). First, hand span was measured as the maximal distance between the tips of the thumb and little finger with the hand opened as wide as possible, and the grip span of the dynamometer was then adjusted according to each player's hand span. This procedure was based on adolescent data showing that the grip span needed for maximal HGS depends on hand span [13]. In practice, the handle was set to the length of each player's fingers so that the grip fitted the hand, and the sex-specific equations of Ruiz et al. [13] were not used. Players were tested in a standing position. Each attempt started with the arm hanging alongside the body, and players raised the fully extended arm forwards to shoulder height (shoulder flexion) while squeezing the dynamometer maximally. We use this movement routinely in our laboratory, but it is not the same as the ALPHA protocol, where the extended arm stays by the side of the body during the squeeze. After a demonstration, they performed two maximal attempts with each hand, as in the ALPHA field-test battery for young people [7]. Since the arm movement was different, the good reliability reported for the ALPHA protocol [6] cannot be assumed for our version of the test, and reliability was not assessed in this sample. Players were told to squeeze as hard as possible without jerking or compensatory movement. Hand dominance was not analyzed because the mean of both hands was used. The right hand was tested before the left, with 30 s of rest between trials. The time between the HGS and isokinetic tests was not recorded. The best value for each hand was kept, and the primary HGS variable was the mean of the best right- and left-hand values (kg). Relative HGS was this bilateral mean divided by body mass ($kg \cdot kg^{-1}$).

2.4. Isokinetic Knee Strength

Concentric quadriceps and hamstring peak torque were measured bilaterally at $60° \cdot s^{-1}$ on a HUMAC NORM dynamometer (CSMi, Stoughton, MA, USA). In a previous study, intrarater reliability for knee extensor and flexor measurements on this device was good to excellent, with intraclass correlation coefficients of 0.74–0.89 [14]. This external evidence supports the use of the device but does not establish the reliability of the present protocol. A velocity of $60° \cdot s^{-1}$ is commonly used to characterize maximal knee extensor and flexor torque in soccer players and youth athletes [2–4,15]. Players warmed up on a mechanical bike for 5 min at approximately 100 W and 70 rpm and then performed 5 min of self-selected dynamic exercises. Then, they were seated on the isokinetic device with the thigh at approximately 85° relative to the trunk, and the dynamometer axis aligned with the lateral femoral epicondyle. Range of motion was set from 0° to 100° of knee flexion. The upper body and the thigh of the tested leg were secured with straps, and the shank was strapped to the lever-arm pad just above the ankle.

Each player first completed five submaximal flexion–extension repetitions for familiarization, followed by three maximal concentric repetitions with each limb, with standardized verbal encouragement. Extension and flexion were performed reciprocally, with 1 min of rest between sets, which is our standard laboratory protocol [16]. However, the order in which the limbs were tested and the rest period between the two limbs were not recorded. Peak torque was the highest torque value given by the HUMAC software (HUMAC2015, version 15.000.0273) across the three maximal repetitions, expressed in

newton-meters (Nm). The software criterion for the constant-velocity part of each repetition was not recorded. Testing followed the procedures of our previous study [12]. Gravity correction was performed according to the manufacturer's recommendations, with the relaxed limb weighed close to full knee extension, but the exact reference angle was not recorded. Lever-arm length was set following the manufacturer's procedures, and the same experienced examiner conducted the set-up and testing. Since we were interested in general lower-limb strength and not in interlimb asymmetry, right- and left-limb peak torque values were averaged separately for the quadriceps and hamstrings. Relative torque was the bilateral mean divided by body mass ($Nm \cdot kg^{-1}$). This conventional ratio was used for comparability with previous soccer strength research [12,16,17], although those studies do not establish that ratio scaling is appropriate. Ratio scaling assumes that strength is directly proportional to body mass and has been shown to overcorrect isokinetic knee torque in female soccer players [18], so the relative analyses were complemented by alternative size adjustments (Section 2.5).

2.5. Statistical Analysis

Analyses were performed in IBM SPSS Statistics, version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables are reported as mean ± standard deviation (SD) and range. Pearson product–moment correlations were calculated between absolute HGS and absolute quadriceps and hamstring torque, and between relative HGS and relative torque, for the full sample and for male and female players separately. Because pooling two groups that differ markedly in body size and strength can inflate correlations, sex-adjusted partial correlations (controlling for sex) were also calculated for the full sample. These are equivalent to pooled within-sex correlations. The contribution of between-sex differences to each pooled association was quantified by partitioning the total sum of cross-products into within-sex and between-sex components. Ninety-five percent confidence intervals (CIs) for r were obtained with Fisher's z transformation. The four correlations within each group (absolute and relative quadriceps and hamstring torque) were treated as one family of tests, so a Bonferroni-adjusted significance level of $p < 0.0125$ was used for the correlation analyses. The conclusions were also checked against a stricter threshold covering all 12 group-specific correlations ($p < 0.0042$). Because the HGS–quadriceps and HGS–hamstring correlations share HGS and were estimated in the same players, they were compared with Steiger's test for dependent correlations [19], and 95% CIs for their difference were obtained with Zou's method [20].

Separate linear regression models were then fitted for each torque outcome, with HGS, chronological age, and sex as predictors. Hierarchical linear regression was used to see whether HGS explained variance in knee torque beyond demographic and anthropometric characteristics. In the absolute models, age, sex (coded 0 = male, 1 = female), height, and body mass formed the first block and absolute HGS the second. In the relative models, age, sex, and height were entered first and relative HGS second; body mass was not entered again, as it was already part of both the predictor and the outcome. The contribution of HGS was summarized by the change in explained variance (ΔR^2), the corresponding F-change test, and the partial correlation between HGS and torque. The residual standard error (root mean square error, RMSE) of the Block 1 and full models was used to describe the error in estimating individual torque values, and the leave-one-out cross-validated RMSE, calculated from the deleted residuals, was used as an internal check of out-of-sample error. R^2 values are reported to three decimal places.

To test for moderation, an HGS × age or an HGS × sex interaction term was added, in separate models, to the fully adjusted models described above. Continuous predictors were standardized (z-scores) before the interaction terms were computed. These eight interaction tests were treated as exploratory and were not adjusted for multiplicity; a

Bonferroni-adjusted threshold for eight tests would be $p < 0.00625$. Biological maturity was not assessed, so it could not be included. Regression assumptions were checked using histograms and normal probability plots of the standardized residuals, the Shapiro–Wilk test on the residuals, plots of standardized residuals against standardized predicted values, Cook's distance, tolerance, variance inflation factors (VIFs), and the modified Breusch–Pagan test. Where residual variance was not constant, the HGS coefficient was re-estimated with heteroscedasticity-consistent (HC3) standard errors. The players came from five teams, but team membership and the number of players per team were not kept in the analysis dataset, so clustering by team could not be modeled. Each team included players of one sex only, which means that part of any difference between teams overlaps with the sex term in the adjusted models. Except for the correlation analyses, statistical significance was set at $p < 0.05$. Since several related models were fitted for each outcome, p-values between 0.0125 and 0.05 were treated with caution and regarded as weak evidence, because they would not remain significant after a Bonferroni adjustment for the four torque outcomes. All variables came from the same preseason session, so the regression models describe cross-sectional associations; they do not predict future performance or injury.

Three sensitivity analyses examined whether the relative findings depended on ratio scaling, which can create or distort correlations when the same denominator is used for both variables [21,22]. First, body mass was added to Block 1 of the relative models. Second, log-linear (allometric) models were fitted with ln(torque) as the outcome, ln(body mass), age, and sex in Block 1, and ln(HGS) in Block 2. These models avoid a shared denominator and assume that strength varies with body mass according to a power function, with the fitted exponent indicating whether ratio scaling (an exponent of 1) is appropriate [23]. The body-mass exponents for torque and HGS were also estimated separately for each sex. Third, the hierarchical models were repeated separately for male and female players, with sex removed from Block 1.

3. Results

Participant characteristics and strength values are shown in Table 1. Mean age was 16.18 ± 1.01 years. Of the 111 players, 35 were 15 years old, 34 were 16, 29 were 17, and 13 were 18. Most of the female players (20 of 30) were 15, and none were 18. The participant-level hamstring-to-quadriceps (H:Q) ratio averaged 0.72 ± 0.09 in male and 0.67 ± 0.09 in female players. Correlations among all study variables are shown separately for each sex in Table A1.

Table 1. Participant characteristics and strength values.

Variable	All (n = 111)	Male (n = 81)	Female (n = 30)
Age (years)	16.18 ± 1.01 (15–18)	16.44 ± 0.97 (15–18)	15.47 ± 0.73 (15–17)
Age distribution, n (15/16/17/18 years)	35/34/29/13	15/28/25/13	20/6/4/0
Height (cm)	172.31 ± 9.42 (151.0–189.0)	176.87 ± 5.75 (163.0–189.0)	160.01 ± 5.58 (151.0–175.0)
Body mass (kg)	65.25 ± 8.94 (44.1–88.9)	68.70 ± 6.71 (52.6–88.9)	55.91 ± 7.44 (44.1–76.4)
BMI (kg·m^{-2})	21.91 ± 1.95 (17.87–29.29)	21.95 ± 1.77 (17.88–26.08)	21.81 ± 2.41 (17.87–29.29)
HGS (kg)	37.13 ± 8.02 (15.75–56.50)	40.62 ± 5.30 (28.00–56.50)	27.68 ± 6.35 (15.75–41.50)
Relative HGS (kg·kg^{-1})	0.57 ± 0.09 (0.30–0.77)	0.59 ± 0.07 (0.44–0.77)	0.49 ± 0.09 (0.30–0.64)
Quadriceps peak torque (Nm)	174.84 ± 41.68 (86.5–251.5)	194.81 ± 26.95 (136.0–251.5)	120.92 ± 21.57 (86.5–179.0)
Hamstring peak torque (Nm)	124.15 ± 34.02 (57.0–214.0)	140.15 ± 22.89 (97.0–214.0)	80.97 ± 17.33 (57.0–132.0)
H:Q ratio	0.71 ± 0.09 (0.53–0.95)	0.72 ± 0.09 (0.53–0.95)	0.67 ± 0.09 (0.56–0.92)
Relative quadriceps torque (Nm·kg^{-1})	2.65 ± 0.41 (1.70–3.55)	2.84 ± 0.29 (2.20–3.55)	2.16 ± 0.27 (1.70–2.72)

Relative hamstring torque (Nm·kg^{-1})	1.88 ± 0.37 (1.18–2.63)	2.04 ± 0.27 (1.53–2.63)	1.44 ± 0.21 (1.18–1.92)

Values are mean ± SD (range), except for the age distribution, which gives the number of players aged 15, 16, 17, and 18 years. HGS and peak torque are the means of the right and left sides. The H:Q ratio was calculated for each player from bilateral mean hamstring and quadriceps peak torque. BMI, body mass index; HGS, handgrip strength; H:Q, hamstring-to-quadriceps.

In the full sample, absolute HGS correlated strongly with quadriceps torque (r = 0.86, 95% CI 0.80–0.90, $p < 0.001$) and hamstring torque (r = 0.74, 95% CI 0.64–0.82, $p < 0.001$) (Table 2). These pooled coefficients were inflated by the large differences between male and female players in both HGS and knee torque (Figure 1). After adjustment for sex, the correlations decreased to 0.68 (95% CI 0.56–0.77) for quadriceps and 0.42 (95% CI 0.25–0.56) for hamstring torque. Between-sex differences accounted for approximately 66% of the pooled covariance between HGS and quadriceps torque and 75% of that between HGS and hamstring torque. Correlations were also lower when both measures were expressed relative to body mass. The pooled relative correlations were 0.69 (95% CI 0.57–0.77) for quadriceps and 0.47 (95% CI 0.31–0.61) for hamstring torque, and the corresponding sex-adjusted values were 0.55 (95% CI 0.41–0.67) and 0.20 (95% CI 0.01–0.37). In male players, all four correlations were weaker than in the pooled sample, and the absolute hamstring correlation was only 0.36 (95% CI 0.15–0.53). In female players, the quadriceps correlations were similar to or higher than the pooled values (r = 0.85 and 0.75), but with wide confidence intervals, whereas the hamstring correlations were lower. The relative HGS–hamstring correlation did not reach the Bonferroni-adjusted level in either male (r = 0.16, $p = 0.145$) or female players (r = 0.33, $p = 0.079$), nor after adjustment for sex in the full sample ($p = 0.035$). All other group-specific correlations remained significant when the stricter threshold for 12 tests was applied.

Table 2. Pearson correlations between handgrip strength and knee peak torque.

Group	Scale	Outcome	r	95% CI	*p*
All (*n* = 111)	Absolute	Quadriceps	0.86	0.80 to 0.90	<0.001
	Absolute	Hamstrings	0.74	0.64 to 0.82	<0.001
	Relative	Quadriceps	0.69	0.57 to 0.77	<0.001
	Relative	Hamstrings	0.47	0.31 to 0.61	<0.001
All, sex-adjusted (*n* = 111)	Absolute	Quadriceps	0.68	0.56 to 0.77	<0.001
	Absolute	Hamstrings	0.42	0.25 to 0.56	<0.001
	Relative	Quadriceps	0.55	0.41 to 0.67	<0.001
	Relative	Hamstrings	0.20	0.01 to 0.37	0.035
Male (*n* = 81)	Absolute	Quadriceps	0.63	0.47 to 0.74	<0.001
	Absolute	Hamstrings	0.36	0.15 to 0.53	0.001
	Relative	Quadriceps	0.47	0.29 to 0.63	<0.001
	Relative	Hamstrings	0.16	−0.06 to 0.37	0.145
Female (*n* = 30)	Absolute	Quadriceps	0.85	0.71 to 0.93	<0.001
	Absolute	Hamstrings	0.64	0.37 to 0.82	<0.001
	Relative	Quadriceps	0.75	0.54 to 0.88	<0.001
	Relative	Hamstrings	0.33	−0.04 to 0.61	0.079

Relative values are expressed per kg of body mass. Sex-adjusted values are partial correlations controlling for sex, which are equivalent to pooled within-sex correlations (df = 108). Within each group, the Bonferroni-adjusted significance level was $p < 0.0125$. CI, confidence interval.

The correlation between quadriceps and hamstring torque was 0.88 for absolute and 0.77 for relative values in the full sample (male players, 0.68 and 0.51; female players, 0.78 and 0.54). After this dependence was taken into account, the HGS–quadriceps correlation

was significantly larger than the HGS–hamstring correlation in the full sample for both absolute values (difference 0.11, 95% CI 0.06–0.19; Steiger's Z = 4.46, $p < 0.001$) and relative values (difference 0.21, 95% CI 0.11–0.33; Z = 4.21, $p < 0.001$). The difference was also significant in male players (absolute 0.27, 95% CI 0.13–0.44, $p < 0.001$; relative 0.31, 95% CI 0.11–0.51, $p = 0.003$) and in female players (absolute 0.21, 95% CI 0.07–0.45, $p = 0.004$; relative 0.43, 95% CI 0.15–0.76, $p = 0.002$), although the female estimates were imprecise.

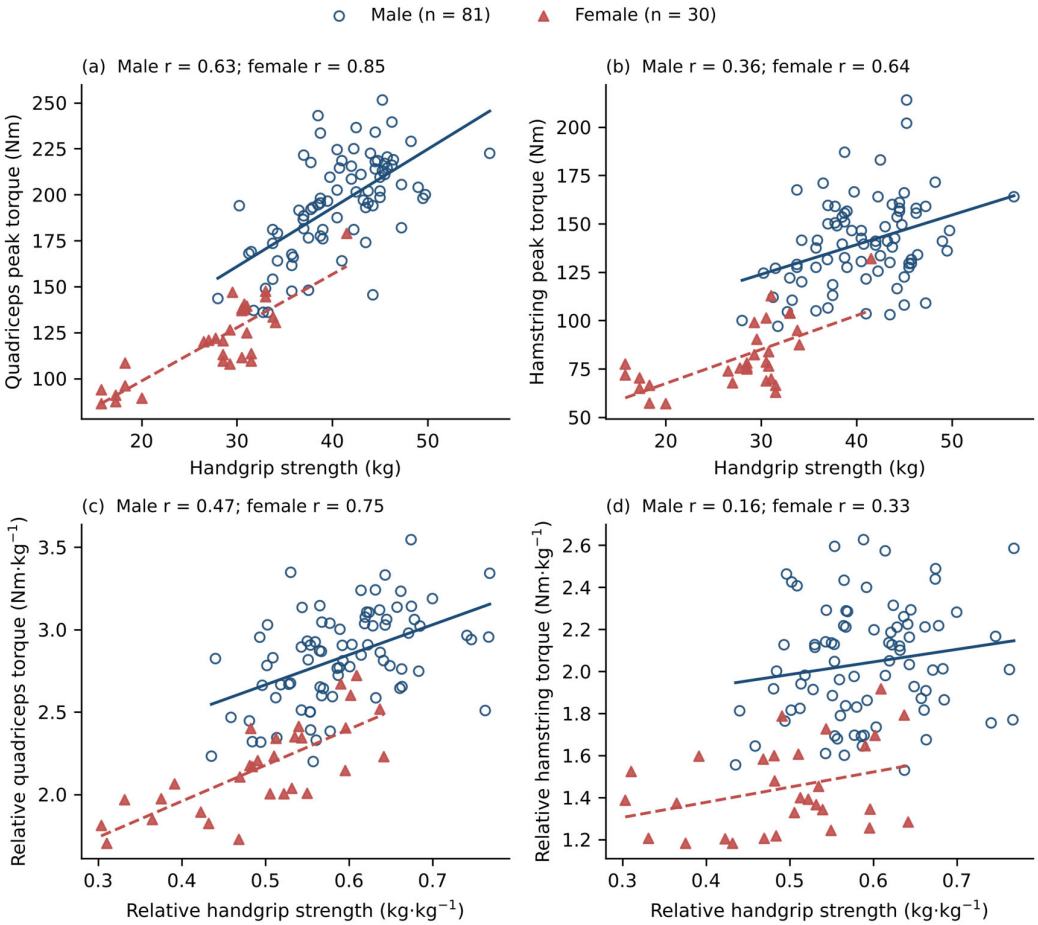


Figure 1. Relationships between handgrip strength and knee peak torque in male (open circles, solid lines) and female players (filled triangles, dashed lines). (**a**) Absolute quadriceps torque; (**b**) absolute hamstring torque; (**c**) relative quadriceps torque; (**d**) relative hamstring torque. Lines are sex-specific least-squares fits, and *r* values are sex-specific Pearson correlations.

In the age- and sex-adjusted models, HGS, age, and sex together explained 80.9% of the variance in absolute quadriceps torque and 68.4% in absolute hamstring torque (Table 3). For players of the same age and sex, each additional 1 kg of bilateral HGS corresponded to 2.97 Nm more quadriceps torque (95% CI 2.33–3.60) and 1.51 Nm more hamstring torque (95% CI 0.84–2.17). The same models explained 68.4% of the variance in relative quadriceps torque and 54.3% in relative hamstring torque. Because relative HGS averaged 0.57 ± 0.09 kg·kg^{-1}, its coefficients are more easily interpreted for a difference of 0.1 kg·kg^{-1}, which corresponded to 0.20 and 0.07 Nm·kg^{-1} for relative quadriceps and hamstring torque, respectively.

Table 3. Age- and sex-adjusted linear regression models of knee peak torque on handgrip strength.

Outcome	HGS B (95% CI)	Age B (95% CI)	Sex B (95% CI)	R^2	Adjusted R^2	RMSE
Quadriceps, absolute	2.97 (2.33 to 3.60)	5.18 (1.31 to 9.05)	−30.44 (−42.01 to −18.88)	0.809	0.803	18.48
Hamstrings, absolute	1.51 (0.84 to 2.17)	4.22 (0.16 to 8.28)	−35.55 (−47.68 to −23.42)	0.684	0.675	19.38
Quadriceps, relative	1.98 (1.43 to 2.54)	0.041 (−0.008 to 0.089)	−0.434 (−0.559 to −0.310)	0.684	0.675	0.234
Hamstrings, relative	0.66 (0.06 to 1.26)	0.026 (−0.027 to 0.078)	−0.505 (−0.639 to −0.371)	0.543	0.531	0.253

Unstandardized coefficients. Sex was coded 0 = male and 1 = female, so the sex coefficient is the adjusted difference between female and male players. HGS coefficients were significant in all models ($p < 0.001$, except relative hamstrings, $p = 0.031$). In the relative models, HGS and torque are expressed per kg of body mass, so the HGS coefficient refers to a difference of 1 kg·kg^{-1}, which is much larger than the variation in the sample (SD 0.09 kg·kg^{-1}). A difference of 0.1 kg·kg^{-1} corresponds to one-tenth of the coefficient (0.20 and 0.07 Nm·kg^{-1} for relative quadriceps and hamstring torque). RMSE, root mean square error (residual standard error, in Nm for absolute and Nm·kg^{-1} for relative outcomes); HGS, handgrip strength; CI, confidence interval.

Age, sex, height, and body mass on their own explained 81.7% of the variance in absolute quadriceps torque and 74.5% in absolute hamstring torque (Table 4), which was more than HGS alone explained in the pooled sample (73.3% and 55.0%). Much of this was due to sex, which on its own explained approximately 63% of the variance in absolute quadriceps torque and 60% in absolute hamstring torque (calculated from Table 1). Within each sex, HGS alone explained about 40% (male players) and 72% (female players) of the variance in quadriceps torque (Table A1). Adding HGS raised the explained variance in quadriceps torque by 5.0 percentage points ($F(1, 105) = 39.35$, $p < 0.001$; partial r = 0.52) and reduced the RMSE from 18.1 to 15.6 Nm. For hamstring torque, the gain was only 0.7 percentage points and was not statistically significant ($F(1, 105) = 3.05$, $p = 0.084$; partial r = 0.17), and the RMSE changed only from 17.5 to 17.3 Nm. In the relative models, HGS added 15.1 percentage points for quadriceps torque ($F(1, 106) = 51.97$, $p < 0.001$; partial r = 0.57) and 2.0 percentage points for hamstring torque ($F(1, 106) = 4.64$, $p = 0.033$; partial r = 0.20). Like the other hamstring results with p-values between 0.0125 and 0.05, this small increment would not remain significant after a Bonferroni adjustment for the four torque outcomes, so it provides only weak evidence of an independent association. Leave-one-out cross-validated RMSEs were close to the in-sample values (15.9 Nm for quadriceps and 17.8 Nm for hamstring torque in the full absolute models), indicating little overfitting. Even so, when the in-sample RMSE of the full models is multiplied by the critical t value (1.98), the approximate 95% range for an individual player is ±31 Nm for quadriceps torque (about 18% of the sample mean) and ±34 Nm for hamstring torque (about 28% of the mean). These ranges are based on the in-sample RMSE and should not be read as formal prediction intervals. Coefficients for all predictors are reported in Table A2.

Table 4. Hierarchical regression models: contribution of handgrip strength beyond age, sex, height, and (for absolute outcomes) body mass.

Outcome	Block 1 R^2	Full-Model R^2	ΔR^2	F Change (df)	p	HGS B (95% CI)	Partial r	RMSE (Block 1/Full)
Quadriceps, absolute	0.817	0.867	0.050	39.35 (1, 105)	<0.001	1.94 (1.33 to 2.55)	0.52	18.15/15.55
Hamstrings, absolute	0.745	0.752	0.007	3.05 (1, 105)	0.084	0.60 (−0.08 to 1.29)	0.17	17.49/17.33
Quadriceps, relative	0.540	0.691	0.151	51.97 (1, 106)	<0.001	2.01 (1.46 to 2.57)	0.57	0.282/0.232
Hamstrings, relative	0.523	0.543	0.020	4.64 (1, 106)	0.033	0.66 (0.05 to 1.26)	0.20	0.258/0.254

Block 1 contained age, sex, height, and body mass for the absolute outcomes, and age, sex, and height for the relative outcomes. Block 2 added absolute or relative HGS. The p-value for ΔR^2 is identical to that of the HGS coefficient. Partial r is the correlation between HGS and torque controlling for the Block 1 variables. RMSE is given for Block 1 and for the full model (Nm for absolute and Nm·kg^{-1} for relative outcomes). In the relative models, a difference of 0.1 kg·kg^{-1} in

relative HGS corresponds to one-tenth of the HGS coefficient (0.20 and 0.07 Nm·kg^{-1} for quadriceps and hamstring torque). HGS, handgrip strength; CI, confidence interval; RMSE, root mean square error.

Residuals from all hierarchical models were approximately normally distributed (Shapiro–Wilk $p \geq 0.30$). No standardized residual exceeded ±3, the largest Cook's distance was 0.11, and the highest VIF was 4.12. The modified Breusch–Pagan test indicated nonconstant residual variance in the absolute ($p < 0.001$) and relative hamstring models ($p = 0.016$), but not in the quadriceps models ($p = 0.126$ and 0.111). With HC3 standard errors, the HGS coefficient remained nonsignificant for absolute hamstring torque (95% CI −0.07 to 1.28, $p = 0.080$) and significant for relative hamstring torque (95% CI 0.03 to 1.28, $p = 0.039$), and the quadriceps results were unchanged ($p < 0.001$).

None of the HGS × sex interactions were significant (absolute quadriceps $p = 0.351$, absolute hamstrings $p = 0.932$, relative quadriceps $p = 0.714$, relative hamstrings $p = 0.905$), but the confidence intervals for the female-minus-male difference in slope were wide. The differences were −0.53 Nm per kg of HGS (95% CI −1.65 to 0.59) for absolute quadriceps torque, −0.05 Nm per kg (95% CI −1.31 to 1.20) for absolute hamstring torque, and 0.21 (95% CI −0.94 to 1.37) and 0.08 (95% CI −1.19 to 1.34) Nm·kg^{-1} per kg·kg^{-1} for relative quadriceps and hamstring torque. Three of the four HGS × age interactions were not significant either (absolute quadriceps $p = 0.297$, absolute hamstrings $p = 0.650$, relative hamstrings $p = 0.678$). The exception was relative quadriceps torque (B = 0.058, 95% CI 0.003–0.113, $p = 0.040$), which should be regarded as an exploratory finding because it was one of eight interaction tests and would not remain significant after Bonferroni correction ($p < 0.00625$). For this outcome, the adjusted slope for relative HGS was 0.14 Nm·kg^{-1} per SD at approximately 15.2 years and 0.25 Nm·kg^{-1} per SD at approximately 17.2 years. No similar pattern appeared in the other models.

The sensitivity analyses led to the same conclusions (Table A3). Adding body mass to the relative models left the HGS coefficients and increments almost unchanged (quadriceps $\Delta R^2 = 0.148$, $p < 0.001$; hamstrings $\Delta R^2 = 0.020$, $p = 0.034$), and body mass itself was not associated with relative torque ($p \geq 0.83$). In the log-linear models, ln(HGS) explained an additional 6.1% of the variance in ln(quadriceps torque) beyond ln(body mass), age, and sex (exponent 0.44, 95% CI 0.32–0.55, $p < 0.001$; partial r = 0.60) and 1.0% of the variance in ln(hamstring torque) (exponent 0.20, 95% CI 0.03–0.37, $p = 0.020$; partial r = 0.22). Adding ln(height) did not change these results. Within each sex, the body-mass exponents for torque were close to 1 (male players, 1.04 and 0.94; female players, 0.98 and 1.10 for quadriceps and hamstring torque), and relative torque was essentially unrelated to body mass ($|r| \leq 0.12$). The exponent for HGS in male players was 0.61 (95% CI 0.34–0.88), so relative HGS was negatively correlated with body mass in this subgroup (r = −0.32). In the sex-specific hierarchical models, HGS added 11.7% ($p < 0.001$) and 25.9% ($p < 0.001$) to the explained variance in absolute quadriceps torque in male and female players, respectively, but only 1.4% ($p = 0.207$) and 4.8% ($p = 0.098$) for absolute hamstring torque.

4. Discussion

This study examined the relationship between HGS and isokinetic knee extensor and flexor torque in adolescent soccer players. Absolute HGS was strongly correlated with both quadriceps and hamstring torque in the pooled sample, but these coefficients were inflated by differences between male and female players, and the strength of the associations depended on the muscle group and on how body size and other participant characteristics were considered. The HGS–quadriceps association was significantly stronger than the HGS–hamstring association in the pooled sample and in each sex. After

adjustment for age, sex, height, and body mass, HGS explained a modest additional 5.0% of the variance in quadriceps torque, whereas its contribution to absolute hamstring torque was small and not statistically significant. There was no evidence that sex modified these associations, although the slope differences were estimated imprecisely, and the single significant age interaction was exploratory. Overall, HGS reflected part of the between-player variation in knee extensor strength, but it cannot substitute for joint-specific assessment of knee strength.

The pooled correlations in this study were higher than those previously reported in adults. Ostolin et al. [10] reported correlations of 0.71 and 0.69 between HGS and knee extension and flexion torque at 60°·s^{-1}, compared with 0.86 and 0.74 in our sample. This difference should not be interpreted as evidence that HGS reflects knee strength more accurately in young soccer players. Our sample included male and female players across four years of adolescence, a period during which body size and strength change rapidly, and the male players were, on average, older, taller, and heavier than the female players. This heterogeneity increases the between-player range of both measures and can increase pooled correlations, and in the present data between-sex differences accounted for most of the pooled covariance. After adjustment for sex, the correlations were 0.68 for quadriceps and 0.42 for hamstrings, and in male players they decreased to 0.63 and 0.36, while the female estimates (0.85 and 0.64) had wide confidence intervals. A similar consideration applies to the youth soccer study by Schulz et al. [9], in which correlations between HGS and jump or sprint performance were obtained across a wider age range of 11–18 years and were moderated by age and maturation. Ostolin et al. [10] also found that one-year changes in HGS explained only a small additional proportion of the variance in changes in isokinetic function. These findings reinforce an important distinction: a strong cross-sectional association does not mean that two tests are interchangeable. HGS and isokinetic dynamometry assess force production in different muscle groups and under different mechanical conditions. Players may rank similarly on both tests while a grip test still fails to identify a specific weakness at the knee.

The adjusted models help clarify how much of the raw association was shared with age, sex, and body size. Strength during adolescence is closely related to these characteristics, and they accounted for a substantial proportion of the variance in knee torque in this sample. Age, sex, height, and body mass alone explained more than 80% of the variance in absolute quadriceps torque, which was more than HGS explained on its own. Adding HGS increased the explained variance by 5.0 percentage points for quadriceps torque but by only 0.7 percentage points for hamstring torque, with the latter increment not reaching statistical significance. However, this comparison holds only for the pooled sample, in which sex alone explained approximately 63% of the variance in absolute quadriceps torque, and it should not be generalized to male or female players separately. Within each sex, HGS alone explained about 40% (male players) and 72% (female players) of the variance in quadriceps torque, and adding HGS to age, height, and body mass increased the explained variance by 11.7% and 25.9%, respectively (partial $r \approx 0.49$ and 0.75). Wind et al. [8] similarly reported that body mass partly explained the association between HGS and overall strength in young people. The present findings extend this observation to knee torque and suggest that the shared influence of body size is important when interpreting the relationship between HGS and hamstring strength.

The present data do not establish why HGS was more closely associated with quadriceps than hamstring torque. The explanations considered below should be regarded as hypotheses, because muscle mass, body composition, maturation, and training history were not measured. Knee extensor and flexor strength do not develop identically during adolescence, and their expression is influenced by growth, training exposure, joint position, and testing conditions [2–4]. Ichikawa et al. [24] identified distinct

hamstring-to-quadriceps profiles in adolescent female soccer players using isometric and isotonic rather than isokinetic assessments. Their findings also support considering extensor and flexor function separately, although they are not directly comparable with isokinetic torque. Čaušević et al. [25] likewise reported more consistent associations of isokinetic quadriceps than hamstring strength with countermovement jump height in elite male players, which suggests that the two muscle groups contribute differently to explosive performance. One speculative explanation is that quadriceps torque, which is produced by a larger muscle group, is more closely related to overall muscle mass, and this may also be reflected in grip strength. However, body size alone is unlikely to explain the difference, since in female players body mass showed the same correlation with quadriceps and hamstring torque (r = 0.73 for both; Table A1) while the HGS associations were different. The quadriceps and hamstring measurements may also differ in reliability. Neither explanation could be tested in the present study. The weak relative HGS–hamstring correlation in male players (r = 0.16) should also be interpreted in light of the scaling procedure. In male players, relative torque was essentially independent of body mass, whereas HGS increased less than proportionally with body mass, so that relative HGS was lower in heavier players. Ratio scaling therefore affected the two variables differently, and the near-zero coefficient may partly reflect this rather than a complete absence of association between grip and hamstring strength.

The age interaction observed for relative quadriceps torque should be interpreted as exploratory. It was the only significant result among eight interaction tests, its *p*-value was close to 0.05, and it would not remain significant after correction for multiple testing. Age was also recorded in completed years, which is a coarse measure across a four-year range, and chronological age from 15 to 18 years does not capture individual differences in biological maturation, which can be substantial among players of the same age [26]. Maturation is associated with grip strength and lower-limb power in adolescents [27], and age- and maturation-related differences in knee torque have been reported in youth soccer [2,3]. Because maturity status was not assessed, the present study cannot determine whether the HGS–torque relationship changes across adolescence. Similar caution is warranted for sex comparisons. The female subgroup included only 30 players, most of whom were 15 years old, which reduced the precision of the sex-specific estimates. Sex differences in strength increase during late adolescence and differ between upper- and lower-limb muscle groups [28]. Accordingly, the nonsignificant HGS × sex interactions, whose confidence intervals were wide, indicate that different slopes were not detected in this sample; they should not be interpreted as evidence that the slopes are identical.

The normalized analyses should be interpreted with the properties of ratio scaling in mind. Dividing two variables by the same denominator can create or distort correlations between the resulting ratios [21,22], so the decrease in the correlations after normalization (from 0.86 to 0.69 for quadriceps and from 0.74 to 0.47 for hamstring torque) cannot by itself quantify how much of the association is explained by body size. The relative findings were therefore checked with models that adjusted for body mass without a shared denominator. Adding body mass to the relative models did not change the HGS increments, and in the log-linear models HGS explained an additional 6.1% of the variance in quadriceps torque but only 1.0% in hamstring torque. The absolute hierarchical models, which include body mass as a covariate, pointed in the same direction. Across scaling approaches, HGS was more closely related to quadriceps than hamstring strength, and its independent contribution to hamstring torque was small. The hamstring results that reached $p < 0.05$ in the sex-adjusted, relative, and log-linear analyses ($p = 0.020$–0.039) were close to the conventional threshold and would not remain significant after correction for multiple testing, so we consider them weak evidence at most. In this sample, knee torque scaled approximately in proportion to body mass within each sex, in contrast with the

overcorrection by ratio scaling reported in elite female players [18]. This suggests that the suitability of ratio scaling depends on the sample and the variable. HGS, in contrast, scaled less than proportionally with body mass in male players, which suggests that allometric approaches may be preferable when variables with different scaling properties are compared [18,23].

4.1. Practical Implications

When laboratory equipment is unavailable, HGS can contribute to general physical profiling because it is quick to administer and, in this sample, was more closely associated with knee extensor than knee flexor strength. Its value for estimating knee strength is nevertheless limited. In the pooled sample, age, sex, height, and body mass, which are readily available, explained more of the variance in knee torque than HGS alone, and adding HGS increased the explained variance by only 5.0 percentage points for quadriceps torque and 0.7 percentage points for hamstring torque, although HGS contributed more to quadriceps torque within each sex. Even for the quadriceps, the residual error of the full model implies an approximate 95% range of about ±31 Nm for an individual player. These associations were estimated and checked within the same sample, and the ability of HGS to identify individual players with low knee strength was not assessed. HGS should therefore not be used as a screening substitute for knee dynamometry. A player with average HGS may still have low hamstring torque, an interlimb asymmetry, or another joint-specific deficit. When the clinical or performance question concerns knee extensor or flexor function, return to play after injury, or limb-specific assessment, the relevant muscle group should be tested directly.

4.2. Strengths and Limitations

A strength of this study is that HGS and knee torque were measured during the same preseason session using standardized procedures, with both absolute and body-mass-normalized values examined. The analysis also extended beyond simple correlations by adjusting for key demographic and anthropometric variables and quantifying the additional variance in knee torque explained by HGS. Both male and female players were included, although the female subgroup was relatively small.

Several limitations should be considered. The cross-sectional design does not permit causal or longitudinal conclusions. No a priori sample size calculation was performed because the sample size was set by the number of players available from the participating teams; the sensitivity analysis indicated that the female subgroup had adequate power only for large correlations. Female players were also younger than male players, and none were 18 years old, so age and sex were partly confounded in the pooled analyses. Age was recorded only in completed years. Biological maturation, training age, playing position, and injury history were not recorded, and fat-free mass was not included in the present dataset, even though bioelectrical impedance data for the female players were reported in our previous study [12]. All of these factors may have influenced the associations we observed. Biological maturation is relevant given its relationship with grip strength and lower-limb power [27]. The data of the female players were also included in a previous publication [12], although the research question and analyses differ. In addition, 12 of the 42 female players who completed the assessments had been excluded in our previous study [12] because they did not complete the preseason preparation, changed teams, had limited playing time, or sustained a contact injury during the preseason. The analyzed players may therefore have been more regular starters or better trained, and some selection bias cannot be ruled out. The associations were estimated and checked within the same sample and were not validated in an independent sample, and the ability of HGS to estimate the knee strength of individual players was not established. The residual errors

and approximate ranges reported here suggest that such estimates would be imprecise. Although the players came from five teams, team membership was not kept in the analysis dataset. Clustering by team could therefore not be modeled, and the uncertainty of some estimates may be slightly underestimated. The reliability of the HGS and isokinetic protocols was not re-established in this sample. A few procedural details were not recorded and could not be recovered, including the time between the HGS and isokinetic tests, the limb order, the rest between limbs, and the exact gravity-correction angle. Procedural factors such as the gravity-correction method, hip angle, and range of motion can influence absolute torque and may partly explain why relative hamstring torque in the male players (2.04 $Nm \cdot kg^{-1}$) was higher than values reported for elite male youth players at the same velocity on the same dynamometer [2]. Averaging the two limbs was appropriate for the study question but may have concealed unilateral deficits. Relative strength was expressed using simple ratio scaling; although the sensitivity analyses gave consistent results, allometric scaling may characterize body-size effects differently in other samples [18,23].

5. Conclusions

In adolescent soccer players, HGS was associated with isokinetic knee torque, and this association was significantly stronger for the quadriceps than for the hamstrings in both sexes. Pooled correlations overstated the associations within each sex. After accounting for age, sex, and body size, HGS explained a small additional part of the variance in quadriceps torque in the pooled sample and a larger part within each sex, but very little of the variance in hamstring torque, and the residual errors indicate that it cannot estimate the knee strength of an individual player with useful precision. HGS may therefore complement general strength profiling, but when knee function is of interest, knee extensor and flexor strength should be assessed directly.

Author Contributions: Conceptualization, K.P. and M.M.; methodology, K.P., E.E. and M.M.; validation, E.E.; formal analysis, K.P., E.E. and M.M.; investigation, K.P. and M.M.; data curation, K.P., E.E. and M.M.; writing—original draft preparation, K.P.; writing—review and editing, E.E. and M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical review and approval were waived for this study due to the following justification: The study received a formal waiver from the Cyprus National Bioethics Committee (Laertou 22, 2365 Ayios Dometios, Nicosia, Cyprus) under protocol code [EEBK EP 2022.01.290]. The waiver was granted on the basis that all four of the following conditions apply: (a) the athletes have already signed an informed consent form allowing their data to be used for research, (b) the data were collected as part of the professional teams' annual routine requirements, (c) the information cannot be linked to any person, and (d) no sensitive personal or medical data were collected.

Informed Consent Statement: Written informed consent was obtained from all players aged 18 years. For players younger than 18 years, written informed consent was obtained from a parent or legal guardian, and the players agreed to take part.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors thank the players, their parents, and the coaches for their participation.

Conflicts of Interest: The authors declare no conflicts of interest.

https://doi.org/10.3390/muscles5040083

Appendix A

Table A1. Correlations among study variables in male and female players.

Variable	1	2	3	4	5	6	7	8	9
1. Age	—	0.24	0.05	0.09	−0.01	0.13	0.09	−0.06	0.18
2. Height	0.17	—	0.56	0.34	0.41	0.45	0.04	0.01	0.16
3. Body mass	0.37	0.58	—	0.64	0.73	0.73	0.08	−0.03	0.12
4. HGS	0.17	0.31	0.44	—	0.85	0.64	0.81	0.56	0.33
5. Quadriceps torque	0.35	0.51	0.71	0.63	—	0.78	0.55	0.65	0.45
6. Hamstring torque	0.26	0.30	0.56	0.35	0.68	—	0.26	0.33	0.75
7. Relative HGS	−0.11	−0.13	−0.32	0.70	0.11	−0.06	—	0.75	0.33
8. Relative quadriceps torque	0.14	0.13	0.02	0.46	0.72	0.41	0.47	—	0.54
9. Relative hamstring torque	0.06	−0.06	−0.04	0.12	0.33	0.80	0.16	0.51	—

Pearson correlations for male players (n = 81) are shown below the diagonal and for female players (n = 30) above the diagonal. Strength values are bilateral means, and relative values are expressed per kg of body mass. The critical $|r|$ for $p < 0.05$ is 0.22 for male and 0.36 for female players. HGS, handgrip strength.

Table A2. Coefficients for all predictors in the full hierarchical regression models.

Outcome	Predictor	B (95% CI)	β	p
Quadriceps, absolute	Intercept	−104.22 (−210.21 to 1.76)	—	0.054
	Age (years)	2.28 (−1.09 to 5.65)	0.06	0.183
	Sex (female)	−19.66 (−31.58 to −7.74)	−0.21	0.001
	Height (cm)	0.44 (−0.19 to 1.08)	0.10	0.168
	Body mass (kg)	1.52 (0.93 to 2.11)	0.33	<0.001
	HGS (kg)	1.94 (1.33 to 2.55)	0.37	<0.001
Hamstrings, absolute	Intercept	−4.26 (−122.35 to 113.84)	—	0.943
	Age (years)	1.66 (−2.09 to 5.42)	0.05	0.382
	Sex (female)	−31.02 (−44.30 to −17.73)	−0.41	<0.001
	Height (cm)	−0.09 (−0.80 to 0.61)	−0.03	0.793
	Body mass (kg)	1.59 (0.93 to 2.25)	0.42	<0.001
	HGS (kg)	0.60 (−0.08 to 1.29)	0.14	0.084
Quadriceps, relative	Intercept	−0.024 (−1.571 to 1.522)	—	0.975
	Age (years)	0.034 (−0.015 to 0.083)	0.08	0.177
	Sex (female)	−0.332 (−0.510 to −0.154)	−0.36	<0.001
	Height (cm)	0.0063 (−0.0016 to 0.0142)	0.14	0.117
	Relative HGS (kg·kg^{-1})	2.01 (1.46 to 2.57)	0.45	<0.001
Hamstrings, relative	Intercept	1.340 (−0.349 to 3.030)	—	0.119
	Age (years)	0.027 (−0.027 to 0.080)	0.07	0.328
	Sex (female)	−0.517 (−0.711 to −0.322)	−0.63	<0.001
	Height (cm)	−0.0007 (−0.0093 to 0.0079)	−0.02	0.870
	Relative HGS (kg·kg^{-1})	0.66 (0.05 to 1.26)	0.16	0.033

B, unstandardized coefficient; β, standardized coefficient. Sex was coded 0 = male and 1 = female. Absolute torque is expressed in Nm and relative torque in Nm·kg^{-1}. In the relative models, a difference of 0.1 kg·kg^{-1} in relative HGS corresponds to one-tenth of the HGS coefficient. HGS, handgrip strength; CI, confidence interval.

Table A3. Sensitivity analyses for the contribution of handgrip strength to knee peak torque.

Model and Outcome	Block 1 R^2	Full-Model R^2	ΔR^2	p	HGS Coefficient (95% CI)	Partial r	RMSE
Relative models with body mass added to Block 1							
Quadriceps, relative	0.544	0.691	0.148	<0.001	2.02 (1.45 to 2.58)	0.57	0.233

Model and Outcome	Block 1 R^2	Full-Model R^2	ΔR^2	*p*	HGS Coefficient (95% CI)	Partial *r*	RMSE
Hamstrings, relative	0.524	0.544	0.020	0.034	0.67 (0.05 to 1.28)	0.21	0.255
Log-linear models							
ln(quadriceps torque)	0.832	0.893	0.061	<0.001	0.44 (0.32 to 0.55)	0.60	0.088
ln(hamstring torque)	0.801	0.811	0.010	0.020	0.20 (0.03 to 0.37)	0.22	0.134
Male players (n = 81)							
Quadriceps, absolute	0.522	0.639	0.117	<0.001	1.95 (1.16 to 2.73)	0.49	16.61
Hamstrings, absolute	0.321	0.335	0.014	0.207	0.57 (−0.33 to 1.47)	0.14	19.14
Quadriceps, relative	0.032	0.291	0.258	<0.001	1.98 (1.24 to 2.73)	0.52	0.245
Hamstrings, relative	0.009	0.036	0.027	0.148	0.61 (−0.22 to 1.44)	0.16	0.272
Female players (n = 30)							
Quadriceps, absolute	0.537	0.796	0.259	<0.001	2.27 (1.44 to 3.10)	0.75	10.48
Hamstrings, absolute	0.547	0.595	0.048	0.098	0.78 (−0.16 to 1.72)	0.32	11.88
Quadriceps, relative	0.004	0.584	0.580	<0.001	2.22 (1.46 to 2.97)	0.76	0.186
Hamstrings, relative	0.046	0.142	0.096	0.100	0.69 (−0.14 to 1.52)	0.32	0.204
Full sample, HC3 robust standard errors							
Quadriceps, absolute	—	—	—	<0.001	1.94 (1.29 to 2.59)	—	—
Hamstrings, absolute	—	—	—	0.080	0.60 (−0.07 to 1.28)	—	—
Quadriceps, relative	—	—	—	<0.001	2.01 (1.42 to 2.61)	—	—
Hamstrings, relative	—	—	—	0.039	0.66 (0.03 to 1.28)	—	—

Block 1 contained age, sex, height, and body mass in the relative models with body mass; ln(body mass), age, and sex in the log-linear models; and age, height, and body mass (absolute outcomes) or age and height (relative outcomes) in the sex-specific models. In the log-linear models, the HGS coefficient is the exponent of HGS. The *p*-value refers to ΔR^2 and is identical to that of the HGS coefficient, except for the HC3 rows, in which it refers to the HGS coefficient with robust standard errors. HC3, heteroscedasticity-consistent standard errors; RMSE, root mean square error of the full model.

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