

Role of age in the prediction of hamstring autograft size in anterior cruciate ligament reconstruction

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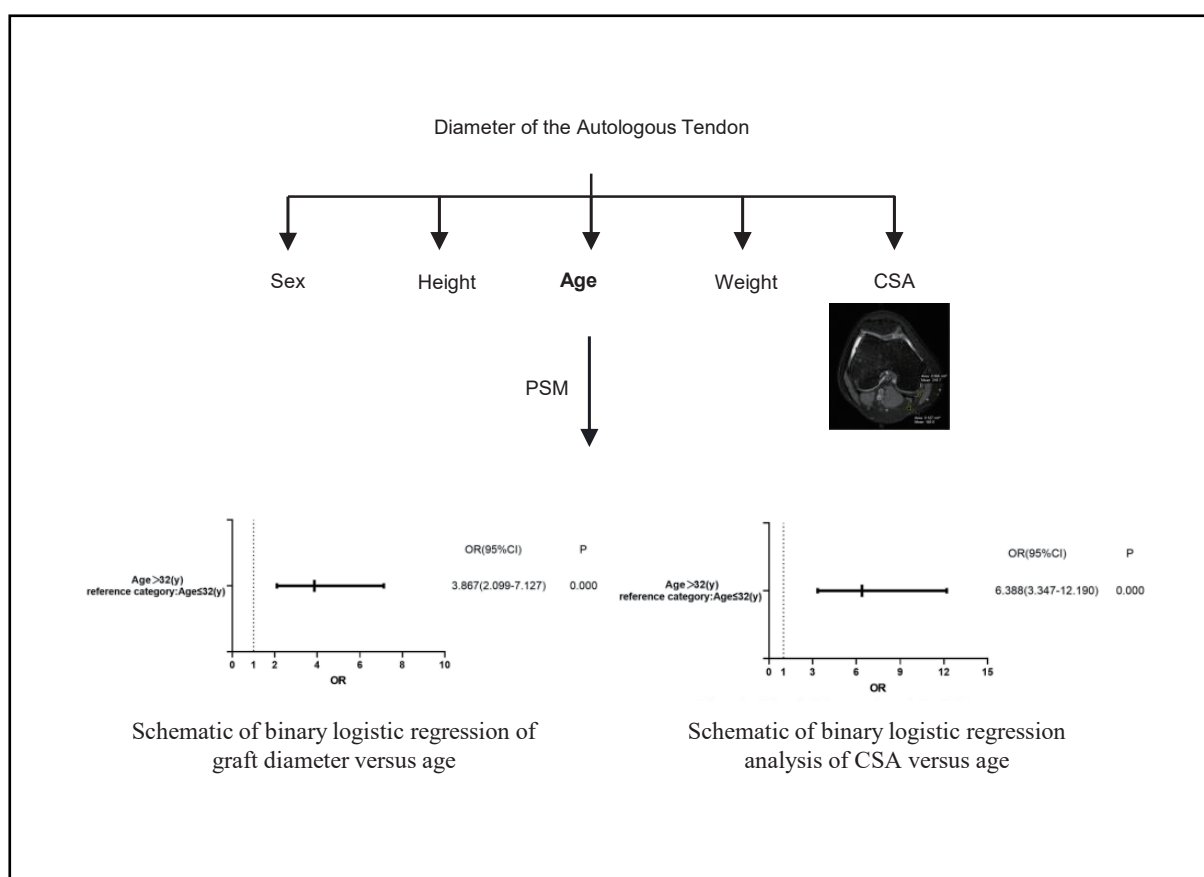
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Graphical abstract



The PSM screening cohort was used to explore the correlation between age and graft diameter and between age and CSA.

Public summary

- This study revealed that graft diameter varies across different age groups.
- Sex, height, and CSA correlate with hamstring tendon grafts, thereby serving as predictive variables for autograft diameter.
- We used PSM to screen the cohort to explore the correlation between age and graft diameter, and the results demonstrated that age can independently influence graft diameter.

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Abstract: *Objective:* While age has been recognized as a noteworthy factor in preoperative graft selection, the correlation between age and hamstring autograft diameter has been the subject of continued debate within the scientific community. This study aimed to explore the correlation between the diameter of autologous tendon grafts and age in anterior cruciate ligament reconstruction (ACLR). *Methods:* A retrospective review of 388 patients who underwent arthroscopic ACLR with hamstring autografts was performed. Patients were grouped by age to analyze differences in hamstring autograft diameter and tendon cross-sectional area (CSA). We explored the correlations between age and graft diameter and between age and the CSA of the popliteal tendon while controlling for the influence of other pertinent variables. *Results:* Compared with female patients, male patients presented significantly greater autograft diameters and hamstring tendon CSAs ($P < 0.05$). Notably, graft diameter and hamstring tendon CSA varied significantly across different age groups ($P < 0.05$); patients aged > 32 years were substantially more likely to have a graft diameter exceeding 8 mm and a CSA surpassing 18.5 mm² than their ≤ 32 -year-old counterparts were ($P < 0.05$). *Conclusion:* This study revealed that graft diameter varies across different age groups, with age independently influencing graft diameter.

Keywords: anterior cruciate ligament reconstruction (ACLR); age; hamstring autograft; graft size; MRI; preoperative planning

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1 Introduction

Anterior cruciate ligament reconstruction (ACLR) is a pivotal intervention that mitigates knee instability following anterior cruciate ligament (ACL) injury^[1]. Graft selection, which is influenced by variables such as patient age, donor site morbidity, and surgeon preference, remains crucial in the preoperative strategy for ACLR^[2]. The hamstring tendon (HT), composed of the semitendinosus (ST) and gracilis tendon (GT), has become the predominant autograft source because of its relatively low risk of destroying bone, reduced risk of impairing knee extension function, and low risk of donor site morbidity compared with bone-patella tendon bone autografts^[3].

The correlation between hamstring tendon graft diameter and consequential strength has been substantiated by previous studies^[4,5]. Furthermore, strategic utilization of larger-diameter grafts has been necessary due to notable reductions in postoperative autograft fracture strength, as documented by subsequent research^[6,7]. The risk of graft failure was significantly reduced when the diameter of the autologous hamstring tendon graft was greater than 8 mm^[8]. Therefore, accurate preoperative assessment of the hamstring tendon graft diameter plays a key role in graft selection.

Current methodologies for predicting the most appropriate graft diameter, including anatomical parameter predictions^[9]

and preoperative ultrasound^[10], magnetic resonance imaging (MRI)^[11–13] or computed tomography (CT)^[14], have their own limitations and variabilities in reliability. While age has been recognized as a noteworthy factor in preoperative graft selection^[12], the correlation between age and hamstring autograft diameter has been the subject of continued debate within the scientific community^[12,15–17]. Given the clinical observation of tendon diameter variability across different age groups, further exploration of the potential correlations with tendon graft diameter is warranted for optimizing preoperative assessments in patients.

The aim of this study was to analyze the variability of intraoperative autografts in diverse age groups undergoing ACLR and to amalgamate other potentially impactful factors pertaining to graft diameter. The primary objective was to discern correlations between graft diameter and age while concurrently investigating other influential factors on graft diameter.

2 Materials and methods

2.1 Participant inclusion and exclusion criteria

The present study included 388 participants who underwent single-bundle ACL reconstruction at our institution between

May 2015 and May 2021. All surgeries were performed by a single surgeon, and patients opted for autografts for anterior cruciate ligament surgery. All patients met either the inclusion criteria or the exclusion criteria. The inclusion criteria were as follows: (i) ACL injury necessitating ACLR; (ii) age $\leq$ 59 years; (iii) complete preoperative imaging, including MRI; and (iv) use of an autologous hamstring tendon braided as a graft. The exclusion criteria were as follows: (i) revision surgery after ACL reconstruction; (ii) combination of other knee injuries resulting in hamstring tendon grafts not being used for ACL reconstruction; and (iii) use of only semitendinosus or gracilis tendons braided as grafts. Patient demographic and clinical characteristics—including sex, height, weight, age at surgery, preoperative knee MRI, and intraoperative graft diameter—were scrupulously documented. This study was approved by the Ethics Committee of the First Affiliated Hospital of University of Science and Technology of China (USTC) (2023-RE-376). Given the retrospective design and de-identification of data, this study was Exempt from informed consent.

2.2 MRI acquisition technique

MRI scans were procured via a 1.5T or 3.0T magnetic resonance detection apparatus (Signa; GE Healthcare), incorporating a knee-specific coil designated for the afflicted limb. The images had a 170 mm field of view with 3-mm slices in a 256 $\times$ 320 matrix. Preoperative coronal T1-weighted images were obtained to visualize the medial femoral epicondyle (ME)^[18]. Subsequent axial proton density images were deployed to optimally delineate the semitendinosus (ST) and gracilis tendon (GT) (visualized in Fig. 1). Sections of the hamstring tendon exhibiting a more circular profile than their distal attachment point were identified as producing reliably reproducible images, thereby being deemed most suitable for measuring the cross-sectional area (CSA). The ICPACS system (GE Healthcare), a “region of interest” tool, enables

manual tracing of the region (i.e., GT + ST), with the software autonomously calculating the cross-sectional area in cm². Two senior radiologists independently and meticulously outlined each tendon within the axial image where the GT and ST boundaries were most distinctly visible.

2.3 Hamstring harvesting procedure

After successful general anesthesia, patients were oriented in the supine position, and an oblique incision was made from the medial 2 cm of the tibial tuberosity. Following the incision of the skin and superficial fascia, the superficial and deep fascia were segregated via vascular clamps. The tendon membrane of the suture musculature was incised to expose the semitendinosus muscle and thin femoral muscle, and the tendon was extracted via a tendon extractor. After the attached muscle tissues were removed via a wide bone knife, an anchor wire was used to braid the two tendons, which were then folded to form a six-strand autologous hamstring tendon (HT) graft. The autologous tendon diameter was ascertained by gauging the smallest aperture through which the autologous tendon could traverse, utilizing a standard tendon gauge incremented by 0.5 mm.

2.4 Statistical methodology

Data were analytically evaluated with SPSS 26.0 software, ensuring alignment with, or approximation to, a normal distribution, and articulating all measures as the mean $\pm$ standard deviation. Categorical variables are reported as numbers and proportions (percentages). To quantify the interobserver repeatability of measurements of cross-sectional areas, a single factor analysis of variance (ANOVA) with repeated measures was used to compute the intraclass correlation coefficient (ICC) for the cross-sectional areas. An independent samples *t* test was used to compare the measurements between the male and female cohorts. Patients were stratified into three age groups: juvenile (0–19 years, group A), young adult (20–39 years, group B), and middle-aged (40–59 years, group C). Single factor ANOVA was used to discern differences in baseline data, graft diameters, and CSA across the age cohorts. Pearson correlation analysis was used to elucidate the correlation between the autologous tendon graft diameter and the body-related base and CSA and to discern the relationship between the CSA and the body-related base in both male and female patients. Binary logistic regression analyses employing propensity score-matched (PSM) cohorts were used to explore the correlation between age and graft diameter and between age and the popliteal tendon cross-sectional area while controlling for the influence of other pertinent variables. Multiple linear regression analysis was used to assess the influence of variables—age, height, weight, and CSA—on graft diameter, from which linear regression equations were derived. Differences were deemed statistically significant at *P* < 0.05.

3 Results

This study included 388 patients, 239 of whom were male (61.4%), ranging in age (32.64 ± 11.58 years) from 14 to 59 years old, with tendon diameters (8.32 ± 0.67 mm) ranging from 6 to 10 mm. The collective data pertaining to the anthro-

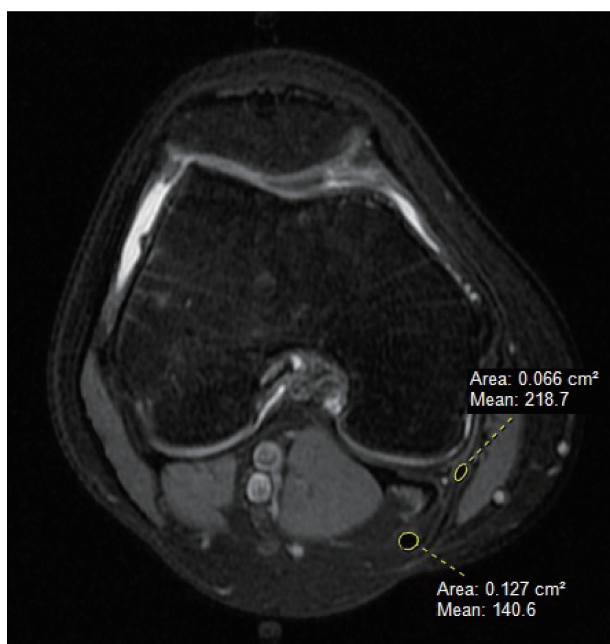


Fig. 1. Measurement of the popliteal tendon cross-sectional area on MRI.

Table 1. Human-related baseline and clinically measured data.

Characteristics	N=388*
Gender	
Men	239(61.60%)
Women	149(38.40%)
Height (m)	1.70±0.09
Weight (kg)	71.71±12.86
Age (years)	32.64±11.58
BMI (kg/m ²)	24.59±3.45
Graft Size (mm)	8.32±0.67
CSA (mm ²)	18.54±4.26

BMI, body mass index. *n(%); M±SD.

pometric-associated foundations and clinical measurements of the participants are shown in Table 1. There was moderate inter-observer reliability for cross-sectional area measurements (ICC=0.721).

Notable differences in the patients' height, weight and BMI, and the diameter and CSA of the autologous tendon grafts were observed between the male and female subjects, and the male participants had significantly greater values ($P < 0.05$). Conversely, the average age at the time of surgical intervention was significantly greater in female participants than in their male counterparts ($P < 0.05$), as shown in

Table 2.

Furthermore, a significant distinction was observed in the CSA and diameter of the graft as well as patient height among the male participants across all age cohorts ($P < 0.05$) (Table 3), whereas the CSA and graft diameter, patient height and BMI were significantly different among female participants across different age groups ($P < 0.05$) (Table 4).

In this study, 239 male patients were included, and Pearson analysis revealed that the graft diameter was correlated with patient height ($r=0.350$), weight ($r=0.361$), BMI ($r=0.219$), and CSA ($r=0.348$), whereas the CSA was correlated with patient height ($r=0.217$), weight ($r=0.324$), and BMI ($r=0.248$). In the 149 female patients included in the study, the graft diameter was correlated with height ($r=0.309$), weight ($r=0.137$), BMI ($r=0.256$), and CSA ($r=0.404$), whereas the CSA was correlated with patient height ($r=0.232$) and weight ($r=0.175$).

Within the male participant cohort, height, weight, age, and CSA were influential factors for the diameter of the hamstring graft, which culminated in the following predictive regression equation for hamstring graft diameter: diameter of the autologous tendon = $2.383 + 2.609 \times \text{height} + 0.009 \times \text{weight} + 0.009 \times \text{age} + 0.033 \times \text{CSA}$. Conversely, within the female participant cohort, only height, age, and CSA influenced the diameter of autologous popliteal tendon grafts, resulting in the subsequent predictive regression equation for hamstring graft diameter: the diameter of the autologous tendon = $-0.220 + 4.318 \times \text{height} + 0.016 \times \text{age} + 0.048 \times \text{CSA}$.

Table 2. Comparison of differences between the male and female groups.

	Gender	n	M±SD	t	Significance
Graft Size (mm)	Men	239	8.58±0.6	11.15	0.00
	Women	149	7.91±0.56		
Height (m)	Men	239	1.75±0.07	21.37	0.00
	Women	149	1.63±0.05		
Weight (kg)	Men	239	76.72±11.67	11.15	0.00
	Women	149	63.68±10.40		
Age (years)	Men	239	30.34±10.56	-4.9*	0.00
	Women	149	36.28±12.14		
BMI (kg/m ²)	Men	239	24.92±3.32	2.39	0.02
	Women	149	24.07±3.59		
CSA (mm ²)	Men	239	20.29±3.90	12.51	0.00
	Women	149	15.75±3.18		

* means that the latter set of values is larger than the former set of values

Table 3. Comparison of data between different age groups of male patients.

	Group A n=39	Group B n=155	Group C n=45	F Value	P Value
	M±SD	M±SD	M±SD		
Graft Size (mm)	8.37±0.70	8.64±0.57*	8.56±0.59	3.092	0.0429
CSA (mm ²)	18.15±2.74	20.84±4.08*	20.24±3.50*	7.869	0.0005
Height (m)	1.77±0.07	1.76±0.06***	1.70±0.06*	20.600	0.0000
Weight (kg)	76.08±12.71	77.62±11.92	74.17±9.48	1.606	0.2029
BMI (kg/m ²)	24.10±3.186	24.94±3.469	25.59±2.778	2.118	0.1225

*Significantly different from Group A ($P < 0.05$); ** significantly different from Group B ($P < 0.05$); *** significantly different from Group C ($P < 0.05$).

Table 4. Comparison of data between different age groups of female patients

	Group A	Group B	Group C	F Value	P Value
	n=23	n=60	n=66		
	M±SD	M±SD	M±SD		
Graft Size (mm)	7.54±0.64	7.90±0.48*	8.05±0.55*	7.446	0.0008
CSA (mm ²)	14.94±2.36	15.16±3.21	16.56±3.26**	4.080	0.0189
Height (m)	1.64±0.05	1.64±0.05***	1.61±0.04*	5.424	0.0053
Weight (kg)	60.61±7.54	64.30±12.47	64.18±9.06	1.189	0.3076
BMI (kg/m ²)	22.56±2.95	23.96±4.30	24.68±2.91*	3.108	0.0477

* Significantly different from Group A ($P < 0.05$); ** significantly different from Group B ($P < 0.05$); *** significantly different from Group C ($P < 0.05$).

We used PSM to control for sex, height, and weight of the patients to derive two cohorts of patients to explore differences in age and graft diameter and the correlation between age and CSA. Differences in sex ($P=0.558$), height ($P=0.591$), and weight ($P=0.493$) between the two cohorts were not significant, but age and graft diameter were significantly correlated. The binomial logistic regression analysis revealed that participants older than 32 years of age were 6.388 times more likely to have a graft diameter larger than 8 mm than were those aged 32 years or younger ($P < 0.05$) (refer to Fig. 2). Additionally, when the correlation between age and CSA was explored, there was no significant difference in sex ($P=0.744$), height ($P=0.797$), or weight ($P=0.970$). The participants aged over 32 years were 3.867 times more likely to have a CSA exceeding 18.5 mm² than were those aged 32

years or younger ($P < 0.05$) (visualized in Fig. 3).

4 Discussion

The optimal graft diameter has emerged as a pivotal factor in preventing procedural failure attributable to diminished graft strength. Researchers reported that 1.7% of patients with hamstring tendon grafts with a diameter exceeding 8 mm experienced graft rupture. In contrast, 6.5% of patients with graft diameters ranging from 7.5–8 mm experienced rupture, whereas 13.6% of those with diameters less than 7 mm experienced rupture^[19]. The most important finding of this study is that age is one of the most important factors influencing the diameter of autologous ligament grafts; patients >32 years old were 6.388 times more likely to have a graft diameter greater

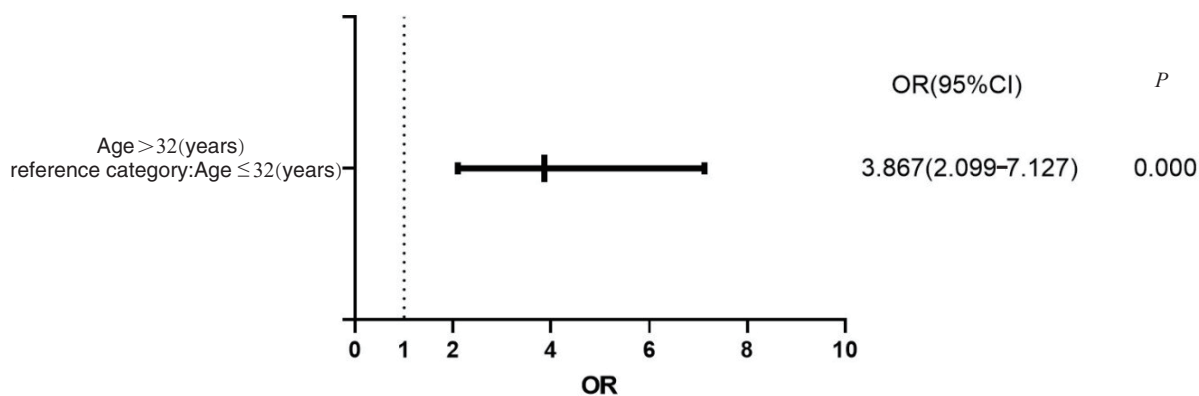


Fig. 2. Schematic of binary logistic regression of graft diameter versus age.

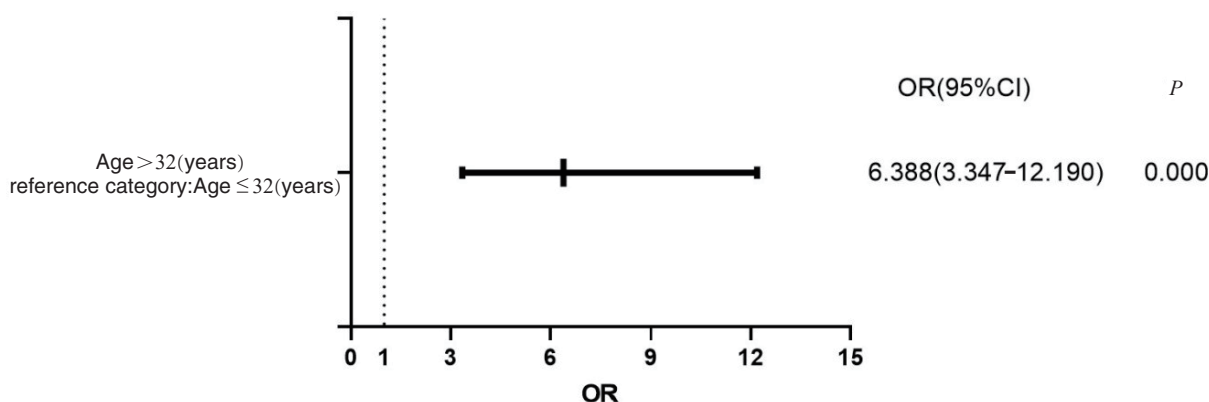


Fig. 3. Schematic of binary logistic regression analysis of CSA versus age.

than 8 mm than patients ≤ 32 years old were, which allows us to select the most appropriately sized autologous tendon for reconstruction on the basis of the patient's age. In previous studies, researchers presented differing perspectives on the relationship between age and tendon diameter. While Grawe et al.^[12] posited that age is a predictor of graft size, Boisvert et al.^[15] did not identify a correlation between age and semitendinosus femoris thin tendon diameter, potentially because their sample included patients under 30 years of age. Pichler et al.^[16] reported no correlation between age and hamstring tendon diameter by dissecting 136 knees of patients aged 49–92 years and measuring semitendinosus and thin femoral tendon diameters; however, the average age of the patients was greater, so it was also difficult to adequately prove their point. Tuman et al.^[17] confirmed a negative correlation between quadriceps semitendinosus and thin femoral tendon diameter and age in females, highlighting the complexity and variability of existing research findings.

Exploring the correlation between the tendon CSA and age, this study confirmed that a larger hamstring tendon CSA significantly correlates with a larger diameter of hamstring tendon grafts, with the present findings validating this correlation ($P < 0.05$). Moreover, the current investigation ascertained the heterogeneity of the CSA among diverse age groups. Among male subjects, the CSA was notably greater in both the young and middle-aged cohorts than in the juvenile cohort. Conversely, female subjects exhibited a significantly greater CSA in the middle-aged cohort than in the young cohort ($P < 0.05$). Age also emerged as an independent correlate of CSA, as substantiated by the binary logistic regression results. Nakagawa et al.^[20] and other scholars reported that the tendon CSA increases with age by examining tendon biomechanics in rabbits in correlation with age. Another study on the aging of tendons in mice suggested that the tendon CSA may remain unchanged with age^[21]. One study on the human tendon CSA revealed that the cross-sectional area of human tendons may increase with age^[22]. While other studies suggest that the cross-sectional area of the human tendon may remain constant with age^[23] and is influenced by an individual's activity level, some studies have shown that younger or older individuals with similar activity levels exhibit similar tendon cross-sectional areas^[24]. In summary, the tendon cross-sectional area does not decrease with age and may increase, which is consistent with our findings.

Notably, decreasing trends in balance and mobility in older adults suggest a concurrent decline in tendon mechanics^[25]. Animal studies illustrate a trajectory where tendon stiffness and strength increase from immaturity to adulthood and wane from adulthood into senescence^[26, 27]. The integrity of tendons, both in terms of modulus and strength, potentially influences balance and mobility and may remain static or decrease with age^[28]. Thus, surgeons, when addressing anterior cruciate ligament injuries in older patients, may consider employing autologous tendon grafts of larger diameters or synthetic ligaments to safeguard sufficient graft strength and curtail procedural failure rates.

In an endeavour to discern correlations between various demographic variables and autograft diameter, the study revealed that sex significantly correlates with graft diameter,

corroborating the findings of prior studies, e.g., Ma et al.^[29] and Janssen et al.^[30]. Moreover, a significant correlation was identified between height and autograft diameter ($P < 0.05$), which aligns with the research outcomes of Tuman et al.^[17], Ho et al.^[31], Xie et al.^[32], and Thomas et al.^[33]. Finally, in males, body weight was significantly correlated with autograft diameter ($P = 0.012 < 0.05$), whereas no such correlation was discernible in females ($P = 0.362$). The opinions of many scholars regarding the correlation between body weight and graft diameter are controversial. Schwartzberg et al.^[9] reported that body weight was the influencing factor with the highest correlation with autologous tendon graft diameter ($r = 0.51$), followed by lower limb length ($r = 0.42$). Xie et al.^[32], Tuman et al.^[17], and Pinheiro et al.^[34] also argued that the correlation between body weight and graft diameter is significant. However, Ma et al.^[29] concluded that there was no correlation between body weight and graft-tendon diameter via linear regression analysis in 536 patients, which is consistent with the findings of Janssen et al.^[30].

Despite the aforementioned insights, the present study is not devoid of limitations, largely stemming from its retrospective nature and reliance on medical records, constraining the assessment of potential predictors such as lower limb length and thigh leg circumference in terms of graft diameter prognostication. In addition, this study was limited by the measurement increments used (0.5 mm). A 7.6 mm-diameter graft would not pass through the 7.5-mm sizer and would therefore be considered an 8 mm graft. A more precise method of determining graft size is needed for more accurate correlation and regression analyses.

5 Conclusions

This study revealed that graft diameter varies across different age groups, with age independently influencing graft diameter. The potential inadequacy of braided autograft tendon diameter necessitates careful consideration during ACLR, especially in younger patients. Sex, height, and CSA correlate with hamstring tendon grafts, thereby serving as predictive variables for autograft diameter and facilitating enhanced preoperative planning and graft selection.

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Conflict of interest

The authors declare that they have no conflict of interest.

Biographies

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