

Original Article

Bilateral Characteristics of the Achilles Tendon and Their Relationship with Jump Performance in University Kendo Athletes

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Abstract

Objectives: This study aimed to examine the morphological characteristics and stiffness of the bilateral Achilles tendon (AT) and jump performance, as well as to investigate the relationship between these factors in male and female university Kendo athletes. **Methods:** Ten male and ten female trained university Kendo players participated in the study. Magnetic resonance imaging was used to capture images of the sagittal and transverse images of the AT, from which the transverse cross-sectional area (CSA), length, and volume were calculated. AT stiffness was also assessed using the MyotonPRO, and rebound jump and single-leg hop performance were measured. **Results:** The maximum CSA of the AT was significantly greater in the left leg than in the right leg ($p < 0.05$). No significant relationship was found between AT characteristics and jumping performance, regardless of gender or whether the left or right leg was considered. **Conclusions:** These results suggest that the characteristic kinematic loading of the left leg during jumping in Kendo may lead to different adaptations in AT morphology between the left and right legs, regardless of gender.

Keywords: Adaptation, Morphology, MRI, SSC, Stiffness

Introduction

The Achilles tendon (AT) is the largest tendon in the human body and requires significant shock absorption and mobility for optimal functioning during activities¹. The AT functions as an attachment tendon for the triceps surae, which connects to the calcaneal tuberosity and transmits the tension from the muscle to the calcaneus. The AT undergoes morphological and mechanical adaptations in response to long-term mechanical loading²⁻⁵. Previous studies have revealed that athletes who habitually load their AT through running and jumping activities have a greater cross-sectional

area (CSA) than healthy individuals^{2,3}. Additionally, the AT has elastic properties, akin to a spring, where it stretches under an external force and returns to its original length once the force is removed. This resistance to deformation is known as stiffness. It has been shown that basketball players possess greater stiffness compared to healthy individuals^{4,5}. Furthermore, AT stiffness affects sports performance, particularly in activities involving the stretch-shortening cycle (SSC) of the muscle-tendon complex, which is essential for jumping and running. Schmidtbleicher (1992)⁶ classified stretch-shortening cycle (SSC) movements into two types: (1) long SSC movement characterized by large angular displacements of the lower limb joints and movement time of more than 250 ms; (2) fast SSC movement with small angular displacements of the lower limb joints and movement time of less than 250 ms. It has been demonstrated that the higher the stiffness, the better the jumping performance, especially with shorter contact time with the ground⁷.

Therefore, the AT tends to increase in CSA and stiffness with prolonged mechanical loading, potentially affecting performance. However, these previous studies only compared groups with differing characteristics and failed

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to account for variations within the groups. For instance, even in healthy populations, the morphology of the AT is significantly correlated with individual height, weight, tibial length, and foot size⁹. To address this issue and illuminate the characteristics of the AT under long-term mechanical loading, it is necessary to investigate the asymmetry in AT properties in athletes who experience chronic loads on only one side. In fact, in athletes who participate in sports with lots of jumping, it has been found that the stiffness of the AT is higher in the jump leg compared to the lead leg⁴. Previous studies have revealed potential gender differences in AT characteristics. Systematic reviews have consistently shown that male tend to exhibit greater AT length, CSA, and stiffness compared to female⁹. Consequently, the evaluation of AT properties should account for gender-specific variations.

Kendo is a sport that involves chronic unilateral loading of the AT. In Kendo, the left leg is placed backwards and used as the jumping leg. The short-duration ankle plantar flexion movement of the jump leg, that is, the SSC, is used to move forward quickly and strike the opponent. This motion imposes a significant tensile load on the left AT and contributes to the high incidence of the left AT injuries in Kendo athletes¹⁰. Thus, there may be left-right differences in the changes in the properties of the AT in kendo athletes, which may also influence SSC performance. Two previous studies investigating AT characteristics in Kendo athletes found that the CSA of the right AT was larger than that of the left AT, which contrasts with findings in other sports^{11,12}. Regarding AT stiffness, one study reported no significant differences¹¹, whereas another indicated higher stiffness on the right side¹², resulting in inconsistent conclusions. Therefore, the asymmetry in AT characteristics among Kendo athletes remains unclear, and the effect of these characteristics on jump performance have not been examined.

Therefore, this study aimed to reveal the bilateral AT characteristics in Kendo athletes using magnetic resonance imaging (MRI) and Myoton PRO, and to determine the relationship between these characteristics and jump performance. It also aimed to examine whether these characteristics and relationships differ by gender.

Materials and Methods

Participants and Protocol

Ten males and ten females trained university Kendo players participated in this study. All kendo players who participated in this study were elite athletes competing at the national level.

The participants were instructed to avoid strenuous exercise for 24 hours prior to the experiment. Initially, basic information such as height, weight, number of years competing, and medical history was collected. After MRI measurements and AT stiffness assessments, the participants performed a thorough warm-up. Subsequently, jump performance tests were conducted.

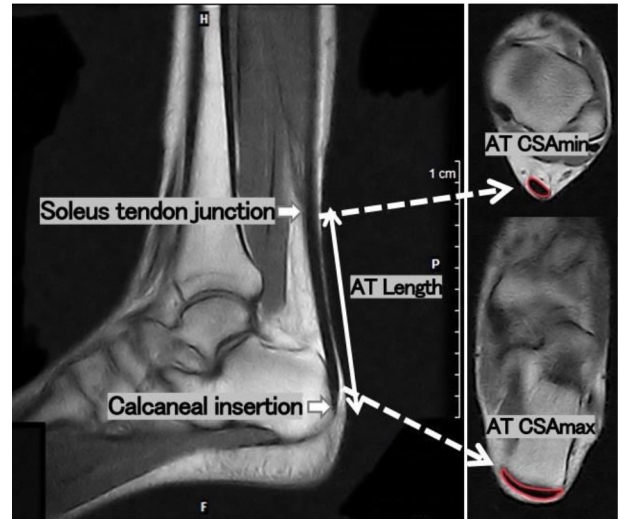


Figure 1. MR sagittal and transverse plane images of the plane Achilles tendon (AT).

Achilles tendon Morphology

MRI scans were performed along the lower leg using a 0.25T MRI scanner (G-Scan brio, Esaote Biomedica). The participants were placed in a supine position with the ankle joint fixed at 0°. Transvers plane images of the AT were obtained using T1-weighted spin echo sequence (SE), repetition time (TR)/echo time (TE): 690/18 ms, field of view (FOV) 240*240 mm, matrix 320*256, slice thickness 8 mm, gap 0.8 mm. Sagittal plane images of the AT were obtained using T1-weighted SE, TR/TE: 350/18 ms, FOV 240*240 mm, matrix 320*272, slice thickness 7 mm, and gap 0.8 mm. The maximum and minimum CSA (CSAmax; CSAmin), length, and volume of the AT were calculated from MRI images using the SliceOmatic analysis software (TomoVision). The AT area analyzed in this study extended from the calcaneal insertion to the soleus tendon junction (Figure 1).

Achilles tendon Stiffness

AT stiffness was measured using the Myoton PRO (Myoton AS, Tallinn). The measurement points were 4 cm (Stiffness-4) and 6 cm (Stiffness-6) proximal to the tendon insertion. The measurements were taken in the prone position with the hip and knee joints in full extension and the ankle joint in dorsiflexion at 0° using a self-made brace. The Myoton PRO mechanically taps the skin with a compression stimulus for 10ms, detecting the resulting damping vibrations using an accelerometer at the device, and measures the deformation properties of tissues within 2 cm beneath the skin. Stiffness (N/m) measured by the Myoton PRO indicates the resistance of the muscle-tendon complex to external forces that attempt

Table 1. Characteristics of the subjects.

	Male		Female		p
	Mean	SD	Mean	SD	
Height (cm)	172.6	7.7	165.4	5.2	0.025*
Weight (kg)	72.5	7.3	61.1	8.0	0.004*
Age (yrs.)	21.2	1.1	20.0	0.8	0.014*
Athletic career (yrs.)	15.1	1.8	14.2	2.3	0.354

Table 2. Characteristics of Achilles tendon and jump performance.

	Male		Female		ANOVA results		
	Right	Left	Right	Left	Interaction effect	Main effect for gender	Main effect for side
AT CSA max	1.28 ± 0.17	1.37 ± 0.20	1.03 ± 0.15	1.27 ± 0.28	F=1.826, p=0.193, partial η^2 =0.092	F=5.154, p=0.036*, partial η^2 =0.223	F=9.253, p=0.007*, partial η^2 =0.340
AT CSA min	0.51 ± 0.10	0.55 ± 0.07	0.48 ± 0.13	0.50 ± 0.11	F=0.258, p=0.618, partial η^2 =0.014	F=0.897, p=0.356, partial η^2 =0.047	F=2.253, p=0.151, partial η^2 =0.111
AT Length	78.2 ± 14.4	77.0 ± 14.9	68.8 ± 16.7	69.4 ± 18.0	F=0.718, p=0.408, partial η^2 =0.038	F=1.433, p=0.247, partial η^2 =0.074	F=0.077, p=0.785, partial η^2 =0.004
AT Volume	6.54 ± 1.92	6.36 ± 1.63	4.26 ± 1.15	4.75 ± 1.26	F=2.973, p=0.102, partial η^2 =0.142	F=8.926, p=0.008*, partial η^2 =0.047	F=0.591, p=0.452, partial η^2 =0.032
Stiffness-4	1542 ± 169	1549 ± 143	1453 ± 228	1586 ± 214	F=2.112, p=0.163, partial η^2 =0.105	F=0.120, p=0.733, partial η^2 =0.007	F=2.631, p=0.122, partial η^2 =0.128
Stiffness-6	1460 ± 133	1503 ± 189	1315 ± 197	1376 ± 192	F=0.045, p=0.834, partial η^2 =0.002	F=3.843, p=0.066, partial η^2 =0.176	F=1.692, p=0.210, partial η^2 =0.086
RJ index	0.66 ± 0.31	0.58 ± 0.18	0.53 ± 0.12	0.53 ± 0.16	F=1.203, p=0.287, partial η^2 =0.063	F=1.208, p=0.286, partial η^2 =0.063	F=0.788, p=0.386, partial η^2 =0.042
RJ GCT	0.25 ± 0.06	0.26 ± 0.05	0.26 ± 0.03	0.26 ± 0.04	F=0.059, p=0.811, partial η^2 =0.003	F=0.046, p=0.832, partial η^2 =0.003	F=0.085, p=0.774, partial η^2 =0.005
RJ height	16.12 ± 5.08	15.97 ± 4.45	13.87 ± 2.47	13.56 ± 2.99	F=0.020, p=0.888, partial η^2 =0.001	F=2.014, p=0.173, partial η^2 =0.101	F=0.165, p=0.689, partial η^2 =0.009
Single-leg hop distance	164 ± 16	168 ± 16	137 ± 18	136 ± 21	F=0.418, p=0.526, partial η^2 =0.023	F=16.790, p<0.001*, partial η^2 =0.483	F=0.307, p=0.586, partial η^2 =0.017

*Statistically significant (p<0.05). CSA ; Cross Sectional Area, AT ; Achilles Tendon, RJ ; Rebound Jump, GCT ; Ground Contact Time.

to alter its contraction or initial shape. The average of three measurements was used as AT stiffness of the participants.

Jump performance

Single-leg rebound jump (RJ) and single-leg hop tests were used to assess jump performance in both legs. Ground

contact time (GCT) and RJ height were measured using a mat switch (Four Assist, Inc.). RJ index (jump height divided by the GCT) was calculated. To measure RJ, the participants were instructed to jump five consecutive times as high as possible, with the shortest ground contact time possible. The maximum value was used for RJ performance. The single-leg hop test required participants to hop forward

Table 3. Correlation coefficient between Achilles tendon characteristics and jump performance in males.

	Right				Left			
	RJ index		SHD		RJ index		SHD	
	r	p	r	p	r	p	r	p
AT CSA max	0.462	0.179	0.174	0.631	0.215	0.551	-0.437	0.207
AT CSA min	-0.381	0.277	0.569	0.086	0.166	0.647	0.288	0.420
AT Length	-0.517	0.126	0.187	0.605	-0.430	0.214	-0.130	0.720
AT Volume	-0.546	0.103	0.36	0.307	-0.164	0.651	-0.417	0.231
Stiffness-4	0.38	0.278	-0.346	0.328	0.285	0.425	0.566	0.088
Stiffness-6	0.428	0.217	-0.011	0.977	0.164	0.651	0.31	0.384

CSA ; Cross Sectional Area, AT ; Achilles Tendon, SHD ; Single-leg Hop Distance.

Table 4. Correlation coefficient between Achilles tendon characteristics and jump performance in females.

	Right				Left			
	RJ index		SHD		RJ index		SHD	
	r	p	r	p	r	p	r	p
AT CSA max	0.427	0.218	0.253	0.481	0.333	0.348	0.401	0.251
AT CSA min	0.599	0.068	0.153	0.673	0.473	0.168	0.23	0.523
AT Length	-0.065	0.859	0.205	0.571	-0.194	0.591	0.413	0.236
AT Volume	0.463	0.178	0.171	0.637	0.115	0.752	0.472	0.169
Stiffness-4	0.753	0.012	0.356	0.312	0.148	0.683	-0.216	0.549
Stiffness-6	0.604	0.064	0.117	0.748	-0.188	0.603	-0.212	0.556

with maximum effort in a single-leg standing posture, and the distance was measured. Each leg was tested three times and the maximum value was used as the measured value. During the measurements, the participants were instructed to place their hands on their hips to eliminate the influence of upper limb movements. No other instructions were given, allowing participants to perform the tests in any manner they preferred. The participants had three trail jumps before the measurements.

Statistical Analysis

Statistical analyses were performed using IBM SPSS version 28 (SPSS Inc.). Normal distribution of all data was assessed using the Shapiro-Wilk test. Two-way analysis of variance (ANOVA) was performed with gender and side (left vs. right) as factors, depending on the normality of the data. Correlations between AT morphology, stiffness, and jump performance (RJ index, single-leg hop distance) were analyzed by gender using Pearson's and Spearman's correlation coefficients, as appropriate. Statistical significance was set at $p < 0.05$.

Results

The characteristics of the participants are shown in Table 1. The height, weight and age were significantly greater in males than in females ($p < 0.05$). The results of the two-way ANOVA, with gender and side (left vs. right) as factors, are shown in Table 2. Significant main effects of gender were observed for AT CSAmax, AT volume, and single-leg hop distance, with males exhibiting higher values in these parameters compared to females ($p < 0.05$). Additionally, a significant main effect of side was found for AT CSAmax, indicating that it was significantly greater in the left leg than in the right leg ($p < 0.05$). There were no significant side-to-side differences in the AT stiffness and jump performance measurements. The interaction effects between gender and side were not significant for any variables.

Correlations between AT characteristics and jump performance in the right and left legs by gender are shown in Table 3 and Table 4. No significant correlations were found for the measurements.

Discussion

This study is the first to demonstrate that AT CSA_{max} is greater in the left leg than in the right leg, irrespective of gender, among university Kendo athletes. However, no other differences were found. Previous research showed that the AT CSA in university Kendo athletes is smaller in the left leg than in the right leg^{11,12}. One possible reason for these inconsistent results is the different AT CSA regions measured. In this study, the AT CSA was measured at the largest and smallest regions, while one of the two previous studies measured it at the myotendinous junction¹¹, and the other used the smallest CSA site in 10%, and 15% of the lower leg length proximal to the insertion of the AT¹². As shown in this study, AT size was not uniform from the origin to the insertion, resulting in significant variations in its CSA depending on the measurement region. Hence, it is necessary to consider the region of morphometric measurements to elucidate the characteristics of the left and right AT more precisely.

In all participants in this study, the AT CSA_{max} was located near the insertion of the distal AT into the calcaneus in this study. The AT CSA tends to increase from proximally to distally, and this change is more pronounced in runners than in non-runners¹³. This suggests that an increase in the AT CSA due to repeated exercise loading tended to occur near the calcaneal insertion site. Kendo players frequently sustain weight on their left foot in a dorsiflexed position, subjecting the distal point of the AT to both tensile forces and compressive stresses as it is pressed against the calcaneal bone¹⁴. In this context, compressive loading stimulates proteoglycan synthesis within the extracellular matrix, promoting an increase in fibrocartilage within the tendon structure¹⁵. A previous study showed that running, repeated SSC movements, could induce the expansion of the fibrocartilage layer at the tendon insertion region, suggesting adaptive changes under chronic mechanical loading¹⁶. Consequently, the left leg jumping motion in Kendo may impose unique mechanical stresses on the distal region of the AT, likely contributing to region-specific increases in the CSA.

Furthermore, the results indicated that the enlargement of CSA occurs irrespective of gender. While AT morphology has generally been reported to be greater in males than in females^{17,18}, significant gender differences observed in the present study may be attributed to differences in body size. Many previous studies, including this one, have consistently reported significant gender differences in height and weight, suggesting that body size may influence AT morphology. Notably, Mansur et al.¹⁹ demonstrated that no gender differences were evident when CSA was normalized by the 3/4 power of body weight. These findings suggest that AT morphology may adapt to loading independently of gender, with physical characteristics playing a role in the extent of this adaptation.

Although no significant difference in AT stiffness was observed between the right and left legs, this finding aligns

with the results of Muraoka et al.,¹² suggesting that the different patterns of leg use in Kendo may not result in side-to-side differences in AT stiffness. In contrast, studies on unilateral jumping events, such as the long jump and high jump, have demonstrated that the jump leg exhibits significantly greater stiffness compared to the lead leg⁴. In jumping events, athletes generate greater ground reaction forces through auxiliary running, which allows them to achieve longer distances. In Kendo, however, the horizontal movement speed is slower than in jumping events. Athletes step off from a stationary position, similar to a single-leg hop, and the load on the AT during this stepping motion is expected to be lower. Nonetheless, the actual load exerted on the AT during stepping motions in Kendo has not yet been measured. Therefore, further studies are necessary to provide a detailed assessment of the mechanical load on the AT in Kendo-specific movements.

In the present study, no significant left-right differences were found in the jump performance of Kendo athletes. The dominant leg, which is used to kick the ball, demonstrated a significantly greater countermovement jump height, jump time, and takeoff velocity than the non-dominant leg in soccer players²⁰. All the participants of the study were asked about their dominant leg as the “kicking ball leg,” with 19 of all subjects answering that their dominant leg was their right leg. The fact that there was no difference in jumping performance between the right and left leg, despite the right being the dominant leg, may be due to the adaptation of Kendo’s characteristic of the left leg being the jump leg, regardless of the dominant leg. In other words, it is possible that the participants’ non-dominant leg acquired the same level of jumping performance as the dominant leg through years of Kendo training.

Several studies have reported significant correlations between AT characteristics and jump performance. Regarding between AT morphology and jump performance, there was a significant correlation between AT volume, drop jump height, power in female volleyball players²¹. In addition, previous studies have reported a relationship between AT stiffness and jump performance, indicating that greater AT stiffness is associated with enhanced jump performance, that is, the greater the AT stiffness, the shorter the ground contact time in drop jumps^{22,23}. However, in the present study, no significant correlations were found between jump performance and AT characteristics by gender for both legs. In Kendo, athletes are required to strike their opponents quickly. Previous research on striking movements in Kendo demonstrated that players with shorter take-off times in their left legs exhibit smaller differences in the timing of extension torque generation across the three lower limb joints²⁴. In contrast, rebound and single-leg hop jumps are characterized by variations in the timing of extension torque generation across the same three joint^{25,26}. These two jumps prioritize height and distance, which do not fully align with the performance demands of Kendo, where minimizing take-off time and maximizing speed is critical. As a result, it is suggested that these jump performance measurements may

not have accurately reflected the specific jump performance required in Kendo, which likely contributed to the lack of a clear relationship between AT characteristics and jump performance in the left leg observed in this study.

Additionally, the fact that nine participants in this study had a history of AT disorders or pain may have influenced this result. Specifically, four men and five women experienced pain in the left AT. It has been reported that even after the symptoms of AT dysfunction improve, functional decline may continue for several years²⁷. Participants who experienced AT disorders or pain in the present study may have had residual functional impairment due to a previous history of AT injuries at the time of measurement, as they were still in high school or had entered university. Therefore, it would be possible to examine the characteristics of the AT and the performance of Kendo athletes in more detail by clarifying the differences in the relationship between AT characteristics and jump performance depending on whether the athlete has a history of AT injuries or not.

In conclusion, the AT CSAm_{ax} on the left leg was greater than that on the right leg in the Kendo athletes. Additionally, there was no significant correlation between the characteristics of the AT and jump performance, regardless of gender or whether the left or right leg was considered.

Ethics approval

The study was approved by the Ethics Committee of the Institute of Health and Sports Sciences, University of Tsukuba (O24-49).

Consent to participate

Written informed consent was obtained from all participants.

Authors' contributions

The study was designed by Nene Iwamoto, who also managed data collection, analysis, and manuscript preparation. Yuji Arita contributed to participant recruitment, data interpretation, and provided support during manuscript preparation. Hideyuki Takahashi played a significant role in study planning, data interpretation, and drafting the manuscript. All authors reviewed and approved the final version of the manuscript, ensuring its quality and coherence.

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