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Review

Long-Term Deficits in Muscle Composition, Performance and Quality of Movement after Achilles Tendon Rupture: A Review

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Abstract: The acute rupture of the Achilles tendon is an increasingly common injury due to an active lifestyle and participation in sports, especially in the middle-aged group. We conducted a focused review of the literature and found that the acute rupture of the Achilles tendon leaves long-term changes in the structure of the triceps surae muscle, regardless of whether it was treated surgically or conservatively. Significant elongation of the Achilles tendon and atrophy of the triceps surae can be observed on the injured leg, even 4 years or more after the injury. The injury also has long-lasting consequences on movement patterns of walking, running and jumping. These compensatory strategies place stress on other musculoskeletal structures, which are then at greater risk for injury.

Keywords: Achilles tendon; tendon rupture; persistent deficits; movement biomechanics; muscle structure; triceps surae

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1. Introduction

Achilles tendon rupture (ATR) is one of the most serious musculoskeletal injuries [1]. ATR can be complete or partial, although the latter is often overlooked. Due to more active lifestyles and greater participation in sports in the middle-aged group, the prevalence of ATR has been increasing since 1980, with a median annual increase of 2.4% [2]. It is a common injury, especially in the physically active population, with an estimated incidence of 5 to 66/100,000 people per year [3]. ATR usually occurs unexpectedly during rapid, explosive movements, most commonly in sports such as basketball, football and racquet sports. The 30–49 age group accounts for 73% of all ruptures in these sports. Typical mechanisms include sudden awkward jumps or lifting heavy loads when the ankle is at the end of the dorsiflexion range [3,4]. The risk may be increased by chronic overuse, degenerative changes and/or associated mechanical disorders. ATR can also occur as a result of a traumatic fall from a great height onto the forefoot, causing forced plantar flexion at the ankle [2–4]. Other risk factors include the oral use of fluoroquinolones and corticosteroids, weight gain and living in an urban environment. The incidence of ATR is higher in men than in women [1].

The treatment of ATR can be either surgical or nonsurgical. Nonsurgical treatment involves wearing a cast or walking boot for 6–8 weeks [3]. ATR treatment can be divided into four phases. The controlled mobilisation phase (0–8 weeks) is the period during which the patient wears a cast or walking boot. This is followed by an early rehabilitation phase (6–11 weeks), when the risk of ATR is highest. The late rehabilitation phase (10–15 weeks) is the time when the calf muscle needs to be strengthened and prepared for more demanding activities. The final phase is the return-to-sport phase (3–12 months). During the first two months, rehabilitation focuses on exercise and then on strengthening the triceps surae and other calf muscles [5]. Choosing the right treatment is critical for return to sport. Several authors agree that despite numerous randomised controlled trials and meta-analyses examining nonoperative and operative treatments, the optimal treatment for ATR is still uncertain [6–9]. In older patients with lower functional requirements or at high risk for surgical complications, conservative nonsurgical treatment is more appropriate [10]. Surgical treatment is mainly used in athletes, as rerupture would be a disaster for the athlete due to the long recovery time. Moreover, several studies have proven and supported that the Achilles tendon is stronger after surgery, which is one of the reasons why they choose this type of treatment [5].

Regardless of the treatment, ATR leaves permanent damage and impairment to the muscle–tendon complex of the triceps surae. Jumping ability is decreased, and walking and running patterns are also altered [3]. The strength of the calf muscles is reduced by 10 to 30%, and significant weakness is also observed during push-off during sports activities. The activation of the triceps surae muscle is proportional to the length of the Achilles tendon ($0.38 < r < 0.52$), suggesting that the loss of functionality of the muscle–tendon complex is due to the anatomical changes left by the injury [2]. Caldwell and Vossler [5] provide timelines for return to sport. These should be 16 weeks for noncontact sports and 20 weeks for contact sports, although these recommendations are not based on evidence. In their article, the authors conclude that the protocol and effectiveness of rehabilitation depend largely on the resources available to professional athletes. They can return to their sport much more quickly than other amateur athletes and the general public.

In a systematic review and meta-analysis, Zellers et al. [11] reported that 15% to 25% of patients with ATR do not return to sports activities. Many of them avoid the sporting activity in which the injury occurred for fear of rerupture. Similarly, Caldwell and Vossler [5] report that 20% of athletes are unable to return to sport, either at the professional or recreational level. Parekh et al. [12] examined the epidemiology and outcomes of ATR in American football players in the National Football League (NFL) in a retrospective study of 31 ATRs over a 5-year period (1997–2002). Nearly 36% of players with this injury never returned to the NFL. Those who did return had a 50% reduction in performance compared with preinjury levels, as indicated by their strength rating scale. ATR can also lead to other musculoskeletal problems, primarily due to changes in the biomechanics of walking. Knee injuries are common, and 25% have Achilles tendonitis. Achilles tendinopathy on the other leg and ATR on the opposite side may occur in 6% [11]. In summary, ATR can have mid-term and long-term consequences that need to be understood in order to develop optimal treatments and strategies to prevent rerupture.

The aim of this article is to provide a brief overview of the deficits that ATR leaves in the long term. This is an important topic because long-lasting changes can negatively affect the quality of an active lifestyle and life in general. The main goal of the article is to answer the following questions: To what extent and in what ways does the injury alter movement patterns? What are the long-term changes in the composition and architecture of the calf muscle? Are there changes in the strength and functionality of the triceps surae complex, and to what extent?

2. Materials and Methods

We searched the PubMed, Web of Science and Scopus databases using the search phrase "Achilles tendon rupture" AND ("long-term follow up" OR "longevity" OR sport* performance OR persistent deficits OR functional deficits). A preliminary search of the available literature in the search engines resulted in 534 results. After a quick review, we selected 67 studies. After reading and reviewing the abstracts, we excluded 31 studies that were relevant to our research questions. The references of the included studies were reviewed to obtain studies that were potentially missed ($n = 3$). We analysed the articles qualitatively to answer our research questions. We also looked at how the studies differed in terms of variables such as population (age, sex, physical activity), measurement methods, time after injury and treatment approach.

3. Results

A total of 30 articles were considered. The studies observed parameters describing the biomechanics of movement, the pattern or kinematics and kinetics of walking and running, the Achilles tendon structure, calf muscle strength, muscle morphology, compensatory properties due to ATR, and changes in various jumping performances. Measurements were taken between 3 months and 14. 5 years after the ATR injury, most commonly 5 years after the injury. In most studies, the subjects were from the general population, with the exception of three studies [13–15] in which the subjects were recreational and professional athletes. The number of subjects was greater than 10 in most studies, with the exception of two studies [14,16] that examined only 1 subject. The studies included mostly male subjects; only a few studies included women, usually in very small numbers. Subjects were on average between 40 and 50 years old, which is likely because most ATR injuries involve men, who are on average between 30 and 49 years [3]. Most of the subjects in the collected studies were treated surgically, but there were some who were treated nonsurgically. An overview of the studies can be found in Table 1. The studies are then briefly summarised in separate sections for each outcome measure.

Table 1. Overview of the study findings.

Authors/Years	Subjects	Variables	Findings
Nilsson et al. (2021) [6]	General population; 76 (22 females, 54 male), 4 years and more from ATR, 4-year follow-up.	Achilles tendon Total Rupture Score (ATRS), strength, endurance, heel-rise height (HRH) and the volume of the calf muscle.	• The average ATRS value was 71.4. • The injured side compared to the healthy leg was still significantly worse in all objective measures. • Noticeable differences were shown in 8.1 ATRS points (95% CI: 6.4–10.6), heel-raise height (HRH) (2.9 cm) (95% CI: 2.2–3.6) and muscular endurance at average heel-raise height (2.7 cm) (95% CI: 2.2–3.3), average repetitions of heel raise (5.0) (95% CI: 3.0–7.1) and cumulative work (807 N) (95% CI: 643–972) • Decrease in calf muscle size compared to healthy side (1.6 cm) (95% CI: 1.3–1.9).
Frankewycz et al. (2017) [17]	General population with ATR: 41 (7 females and 34 males). General population control group: 36 (22 females and 14 males) 2.2–11.5 years after surgery for ATR.	Achilles tendon rerupture, biomechanical properties, elastic properties, cross-sectional area (CSA).	• Tendons with healed ATR have a long-term reduction in elastic properties compared to the opposite side, even after a long healing period. The difference in the elastic properties of the Achilles tendon in ATR is mainly observed in the middle part of the Achilles tendon, the area where most ruptures occur.
Baxter et al. (2018) [16]	A 27-year-old man (1.83 m, 84 kg), ATR on the right side, open surgery, unable to participate in recreational activities due to loss of strength, no pain, 2.5 years after ATR injury.	Fascicle length, pennation size, calf muscle volume, physiological cross-sectional area (PCSA), strength, power, torque and force.	• Architectural differences in the medial head of m. gastrocnemius, compared to a healthy leg (reduced fascicle length for 59%, increased pennation size for 162% and reduced muscle size for 24%). • Decreased PSCA for half compared to the healthy leg. • Decreased isometric strength of plantar flexors for 47% compared to the healthy leg. • There were significant differences in plantar flexors during single-leg raise and isometric strength measurements, but no such differences were seen in walking. ATR fascicles shortened by 63%; idle length was the same. • Motion, torque and plantar flexion during walking (1.05 m/s) similar on both sides. A strong deficit is observed in the single-leg raise, where muscle shortening is also noticeable (70% worse, raise only 11.9°). • Measured 82% fascicle shortening in the medial gastrocnemius measured by ultrasound during single-leg toe-off.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Stäudle et al. (2021) [18]	General population; 11 males, aged 20 to 60.2, 7 years after surgery for ATR.	Muscle–tendon unit (MTU), mechanical properties of m. gastrocnemius medialis.	• Two to seven years after ATR surgery, patients have longer (13% ± 10%), larger (105% ± 28%) and stiffer (54% ± 24%) m. gastrocnemius medialis tendon on the injured side compared with the healthy side. • The muscle fascicles were shorter (32% ± 12%), with larger pennation angles (31% ± 26%). • The average plantar flexion moment deficit was 31% ± 10%.
Wenning et al. (2021) [19]	General population; 52 (30 with anatomical reconstruction, 22 with conventional repair), male, younger than 60 years, 3.5 ± 1.4 years after ATR surgery.	Muscle performance test, maximal isokinetic strength, heel height in the HRH test, gait analysis.	• Deficit in plantar flexion strength for 10.2% 3.5 years after ATR surgery. • An analysis of the maximum torque angle and the deficit in intensity, relative to the plantar flexion angle, showed that these deficits are not evenly distributed over the whole ROM. • Anatomical reconstruction showed a significantly smaller deficit at 10° plantar flexion compared to conventional reconstruction (13.9% vs. 29.9%).
Nicholson et al. (2019) [20]	General population; 12 (10 males, 2 females), 43.3 ± 13.6 years old, 4.4 ± 2.6 years (0.7–9.4) after ATR surgery	ATRS, muscle morphology, gait analysis, muscle strength, ROM of the ankle and hip joint	• Compared to the uninjured side, the ATR side showed shorter muscle fascicle length (12.1–19.6%), increased pennation angle (18.0 ± 22.14%), decreased muscle thickness (9.1–20.1%) and increased CSA of the AT (46.7 ± 34.47%). • A lower jump height (−12.6 ± 15.68%) and longer contact time at the landing (5.5 ± 5.7%) were observed in the countermovement jump (CMJ). • Reduced internal and external rotation of the ROM at the hip joint was also observed. • There was no significant difference in ROM of plantar flexion, intensity or characteristics of gait analysis. • Good ATRS scores were present (mean: 87.9 ± 16.2, range: 43–100), but these were largely dependent on time since surgery.
Heikkinen et al. (2017) [21]	General population; 55 (48 males, 27 females), 38 ± 8 years old, 14 ± 0.5 years after ATR surgery.	Muscle morphology, ROM of plantar flexion, strength and power of the calf muscle	• Longer Achilles tendon on the injured side on average (12 mm) (6%). Decreased mean volumes of m. soleus (63 cm^3), m. gastrocnemius medialis (30 cm^3) and m. gastrocnemius lateralis (16 cm^3) on the ATR side. • Increased volume of m. flexor hallucis longus (5 cm^3) on the ATR side (compensation hypertrophy of the m. flexor hallucis longus). • Plantar flexion strength for the whole ROM decreased by 12% to 18% on the injured side.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Brorsson et al. (2018) [22]	General population; 66 (53 males, 13 females), 50 ± 7 years old, 7 ± 1 years after ATR, 34 surgical, 32 nonoperative.	Calf muscle performance, HRH, ATRS, limb symmetry Index (LSI), Physical Activity Scale (PAS).	• Seven years after ATR, the injured side showed deficits in all tests of calf muscle function (p < 0.001–0.012). • Heel-rise height increased from a mean lift height of 10.8 cm at 1 year postoperatively to 11.5 cm at 7 years. • The mean ATRS was 96 (0–100) and PAS was 4 (0–6). • There were no significant differences between patients with operative treatment and nonoperative treatment, except for the LSI in heel rise repetition at 7-year follow-up.
Zallers et al. (2021) [9]	General population; 11 (10 males, 1 female), 43.6 ± 2.7 years old, 1 to 3 years after ATR, all treated surgically.	Biomechanics of heel rise and jump, ability to return to sport.	• They found that on the ATR side, the vertical shift changed during the single-leg heel lift (mean difference -12.8%), but this was not observed during the jumping task (p > 0). • Decreases on the ATR side in the maximum plantar flexion angle at the ankle in the concentric phase of all tasks (range of mean difference from −19% to −48.8%; p < 0.05) and total plantar flexor work (mean difference range −9.5% to −25.7%; p < 0.05) compared to the healthy side.
Olsson et al. (2011) [23]	General population; 81 (67 males, 14 females) 42 ± 9.1 years old, 1 year and then 2 years after ATR, 42 surgical 39 nonoperative	Achilles tendon rerupture, PAS, ATRS.	• There were no reruptures or other clinical complications between the first and second years of follow-up after ATR. • Statistically speaking, there was little improvement between the 1- and 2-year follow-ups. • The PAS test score was significantly lower compared to preinjury levels, but the ATRS score was relatively high in both groups (89 and 90).
Walker et al. (2020) [24]	General population; 12 (10 males, 2 females), 43.3 ± 3.6 years old, 4.4 ± 2.6 years after ATR surgery	Muscle torque, joint moment, angular velocity, plantar flexion endurance moment, muscle strength.	• The results of the study showed significant main effects on the injured versus uninjured leg regarding the average joint moment. The maximum moment and angle of the maximum moment did not show any difference. The normalised moment curves showed a significant main effect of limb, angular velocity and knee joint position on joint moment in different ROM positions. Significantly higher plantar flexion moment capacity under different test conditions on the undamaged side. • In subjects who underwent surgery for ATR, no limb-to-limb difference was observed in discrete isokinetic strength scores, which is often observed in previous literature. Instead, temporal analyses were needed to highlight the reduced ability of the injured leg to generate joint moments and to maintain a higher level of joint moment for longer.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Jandacka et al. (2017) [13]	Athletes; 22 (16 males, 6 females), aged from 22 to 55 years, half 6 ± 3 years after ATR surgery, half control group	Running kinematics, ankle ROM, maximum ankle moment.	• Athletes with ATR had reduced ankle ROM in the second half of the running phase (Δ7.6°) compared to control group. • During initial contact, the knee was overextended (Δ5.2°). • Increased knee ROM (Δ4.4°) on the ATR side in the first half of the running phase. • In athletes with ATR, the peak hip joint moment increased by 22% on the opposite side of the injured leg compared to the healthy control group.
Horstmann et al. (2012) [7]	General population; 63 (48 males, 15 females), 35.5 ± 6.6 years old, 10.8 ± 3.4 years after ATR surgery.	Muscle strength, muscle endurance (ME), muscle activation ATR, ankle ROM, HRH, calf muscle volume, ankle torque.	• They found that 10 years after ATR, ankle ROM, HRH and calf muscle volume were lower on the injured side than on the opposite leg. • Ankle torque during concentric dorsiflexion at 60°/s and 180°/s and ankle torques during eccentric plantar flexion and concentric plantar flexion at 60°/s were much lower on the injured leg than on the contralateral leg. • Total work was 14.9% lower in the injured leg when isokinetic plantar flexion was measured at 180°/s. • During dorsal flexion, the muscle activity of the m. gastrocnemius was much higher than on the uninjured side. • The limited ROM of the ankle and the increased muscle activity in the injured leg suggest compensatory mechanisms due to differences in muscle morphology and physiology resulting from ATR.
Wenning et al. (2021) [19]	General population; 52 (male only), 41 ± 9.5 years old, 3.5 ± 1.4 years after ATR surgery	Functional performance testing, neuromuscular activation, isokinetic power, HRH, gait kinematics.	• An isokinetic test showed a greater activation integral in all triceps surae muscles on the injured side during active dorsiflexion (eccentric loading of the injured leg). • No significant differences were observed for concentric plantar flexion. • Dynamic heel-rise testing showed greater activation under concentric and eccentric loading for all posterior muscles on the injured side. Meanwhile, a static heel rise for 10 s showed much greater activation. • In gait analysis, there was a much greater preactivation of m. tibialis anterior in the leg phase before ground contact on the injured side. However, in m. gastrocnemius, both the lateral and medial head of the injured side showed much greater activation during the pushing phase.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Willy et al. (2017) [25]	General population; 34 (31 males, 3 females), 48.3 ± 10.9 years old, 6.1 ± 2.0 years after ATR surgery. Half treated surgically, half treated nonoperatively.	ATRS, HRH, kinetic and kinematic analysis of walking, running and jumping, LSI.	• There were no significant differences between the group treated operatively and nonoperatively. • There was a deficit on the injured side in plantar flexion angle during walking, running and jumping (LSI: 53.5% to 73.9%). • The only deficits in angular velocity were observed in running (LSI: 93.5%) and jumping (LSI: 92.5%). • This pattern was accompanied by an even greater deficit of the injured leg in eccentric (LSI: 80.8% to 94.7%) and concentric (LSI: 82.2% to 84.7%) ankle joint strength when performing all tasks. • Patellofemoral joint load was higher in the weighted leg during running (LSI: 107.5%) and jumping (LSI: 107.1%), while only jumping had a higher patellofemoral joint load (LSI: 110.9%).
Speedtsberg et al. (2019) [26]	General population; 34, 45 ± 7 years old, 4.5 years after ATR, treated non-operatively.	Kinetic and kinematic analysis of gait, balance, dynamic stiffness.	• The maximum dorsal flexion was 13.4% higher in the injured leg (16.9 ± 3.1 vs. 14.9 ± 0.4, respectively; $p < 0.001$). • The total positive plantar flexion work was 23,9% higher in the uninjured leg than in the injured leg (4.71 ± 1.60 vs. 3.80 ± 0.79 J/kg). • The quasi-stiffness was higher in the uninjured leg than in the injured leg during the initial (0.053 ± 0.022 vs. 0.046 ± 0.020 N m/kg/°) and subsequent (0.162 ± 0.110 vs. 0.139 ± 0.041 N m/kg/°) phases of eccentric loading. • In the single-leg stance, no difference in swing length was found between the injured and uninjured leg (1.45 ± 0.4 vs. 1.44 ± 0.4 m).

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Agres et al. (2015) [27]	General population; 20 (16 males, 4 females), 45.6 ± 12.3 years old, 2–6 years after ATR surgery.	Tendon stiffness, tendon length, kinematic gait analysis.	• The tendon stiffness ratio between the injured and uninjured Achilles tendon was negatively correlated with the maximum plantar flexion moment during walking ($r = -0.509$, $p = 0.011$). • Similar comparisons with moments of dorsal flexion ($p = 0.325$), eversion ($p = 0.344$), inversion ($p = 0.408$), internal rotation ($p = 0.318$) and external rotation ($p = 0.472$) were not significant. • No significant correlations were also found between tendon stiffness and ankle angle kinematic parameters. • Achilles tendon length ratios at rest between the injured and uninjured side were negatively correlated with the maximum angle of eversion during walking ($r = 0.386$, $p = 0.046$). No correlations were found between the ratios of Achilles tendon length parameters and ankle moments between the injured and uninjured leg. • This suggests that on the injured side, the greater stiffness of the Achilles tendon, rather than the longer Achilles tendon, contributes to the plantar flexion moment deficit.
Zallers et al. (2019) [28]	General population: 21 (11 with ATR and 10 with healthy Achilles tendon), 1–3 years after ATR surgery.	ATRS, PAS, tendon structure, triceps surae structure, muscle activation, kinetic and kinematic analysis of the jump.	• There was no significant difference between the groups in jump height and absolute leg work. During push-off, the knee performed more ($p < 0.001$) and the ankle performed less concentric work ($p < 0.001$), and the rate of EMG rise of the m. gastrocnemius lateralis was greater ($p = 0.02$) on the injured side. • During landing, the knee performed more eccentric work ($p = 0.033$), and the amplitude of activation of m. gastrocnemius lateralis ($p = 0.003$) and m. soleus ($p = 0.02$) before landing was greater on the injured side. • This shows that individuals with ATR shift the work to the knee and change the muscle activation strategy. Differences in the activity of the lateral gastrocnemius may indicate that it is in a good position to generate power during take-off and, together with the m. soleus, assists landing. • The lack of change in muscle activation and reduction in the cross-sectional area of the medial gastrocnemius suggests that this muscle is atrophying and not adapting to the jumping task.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Kauranen in Leppilahti (2001) [29]	General population; 90 (76 males, 14 females), average age 43.1 years, average 3.1 years after ATR surgery.	Reaction time, speed of movement, tapping speed, coordination.	• There were no statistically significant differences between the injured and noninjured legs in the measured parameters of the different motor aspects of the foot (reaction time, speed of movement, tapping speed and coordination). The speed of movement tended to be lower on the injured leg, but not statistically significant ($p = 0.088$).
Brorsson et al. (2017) [8]	General population, 17 with <15% difference in heel rise (15 males and 2 females, aged 40 ± 5 years, 6.2 ± 2.1 years after ATR), 17 with >30% difference in heel rise (16 males and 1 female, aged 56 ± 9 years, 5.9 ± 1.9 years after ATR)	HRH, LSI, ATRS, PAS, ME, calf muscle volume, kinetic and kinematic of the gait, running and jumping.	• The >30% group (30% greater leg difference in heel rise) had significantly more deficits in ankle kinetics in all activities compared with the <15% group (15% less leg difference in heel rise) at a mean of 6 years post-ATR (LSI, 70%–149% and 84%–106%, respectively). • The >30% group had significantly lower scores in heel-rise height compared with the <15% group (LSI, 72% and 95%, respectively; $p < 0.001$) and heel raises (LSI, 58% and 91%, respectively) and a greater difference in Achilles tendon length compared to the healthy leg (114% and 106%, respectively). • Achilles tendon length was weakly associated with ankle kinematic variables ($r = 0.38$–0.44). • LSI in tendon length was negatively correlated with LSI heel rise height ($r = 0.41$).
Don et al. (2006) [30]	General population; 49 (27 males, 22 females), 30 ± 5 years old 3 months, 6 months, 1 year, and 2 years after ATR surgery.	Ankle ROM, muscle stiffness, muscle strength, isokinetic measurements, kinetic gait analysis.	• They found that ankle ROM, plantar flexor passive stiffness and concentric strength recovered within one year. • Gait abnormalities associated with these factors took longer to disappear due to the presence of irregular muscle patterns. • After 2 years, there was still a deficit in eccentric strength of the calf muscles, which affected adaptive gait shifts involving ankle movement and coordinated muscle activity.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Stäudle et al. (2022) [31]	General population; 9 males, 45 ± 9 years old, at least 2 years after ATR surgery.	Kinematics of the lower limbs, morphological characteristics of muscle and tendon.	• The kinematics of the lower limbs were very similar when comparing the injured and uninjured legs. In ATR, a typical characteristic remodelling of the musculotendinous unit (MTU) was observed in the standing phase, corresponding to a lengthening of the series elastic element (SEE) (energy storage) and shortening of the SEE (energy release), with shortened fasciae of the medial m. gastrocnemius (36%) and larger pennation angles (8° and 12°). • Given the optimal length of the force producing fascicles, the fascicles operated at a comparable length on both sides. • The fascicle contraction velocity did not differ between the two sides, except at the time of maximum SEE length, where it was 39 ± 49% lower in the ATR leg. • At the same time, fascicle rotation during contraction was greater on the injured leg throughout the standing phase, and the architectural gear ratio—AGR—was greater during SEE extension.
Follak et al. (2002) [32]	General population; 30 (24 males, 6 females), average age 35.6 years, average 2 years after ATR surgery.	Calf muscle volume, tendon length, kinetics and kinematics of gait.	• Two years after ATR, the Achilles tendon length is on average 1.7 cm longer, but the atrophy of the calf muscle is still noticeable (on average 1.8 cm^3 less volume). • Gait analysis showed a significant deficit in functional mobility in the swing phase, which is reflected as a reduction in active heel lift.
Jandacka et al. (2013) [14]	Recreational athlete (runner), 31-year-old male (1.84 m and 83 kg), ATR on left side, treated operatively, 4-year follow-up after ATR injury.	Tendon length, calf muscle volume, aerobic capacity, kinetic and kinematic analysis of gait.	• During running, the injured atrophied limb showed a functional deficit compared to the uninjured limb. • The length of the Achilles tendon was 3.5 cm longer on the injured side compared to the uninjured side. • The net strength of the ankle joint and plantar flexors in the standing phase is greater on the uninjured side. • The plantar flexion moment was on average −10.85% lower on the injured side in the first measurement and −15.78% lower in the second measurement. • The positive mechanical force in plantar flexion in concentric contraction in the joint on the side of the injury is significantly lower by −13.98% in the first measurement and by −18.54% in the second measurement than in the uninjured joint.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Kastoft et al. (2022) [33]	General population; 34 (28 males, 6 females), average age 45 years, 4.5 years after ATR, divided into two groups (16 control group, 18 subjects), treated nonoperatively.	Tendon length, Achilles tendon resting angle (ATRA), foot pressure analysis.	• They found that the injured Achilles tendon was lengthened by 1.7 cm compared to the healthy leg. • No significant differences were found in the peak forefoot load, peak medial and lateral loads, peak heel load or relationship between Achilles tendon length and peak load measurements. • Dorsal flexion on the injured leg was 1.9° greater (SD 1.28), ATRA was 8.1° greater (SD 6.7) and calf muscle volume was 1.6 cm^3 smaller (SD 1.1).
Leppilahti et al. (2000) [15]	Athletes; 85 (66 recreational, 19 professional), 73 males and 12 females, average age 38.5 years, average 3 years after ATR surgery.	Calf muscle size, muscle strength, isokinetic muscle strength, CSA of the calf muscle, torque and velocity of the calf muscle.	• Isokinetic strength was excellent or good in 73%, while only 30% had normal calf muscle size. • The average maximum plantar flexion torque per unit transverse muscle area was higher on the injured side compared to the non-injured side. • The mean deficit in cross-sectional area (CSA) of the calf muscle was 15% compared with the uninjured leg. The mean peak torque deficit of the planted flexors was speed-dependent and was 9%, 10% and 2% at 30, 90 and 240°/s, respectively.
Metz et al. (2011) [34]	General population; 36 (27 males, 9 females); age range 23–57, divided into rerupture (n = 13) and control (n = 23) groups; 8.7 years follow-up.	Isokinetic muscle strength.	• Isokinetic plantar flexion strength was more or less restored in rerupture group; however, some functional deficits (self-reported) persisted nonetheless.
Westin et al. (2018) [35]	General population, 20 participants with rerupture (16 males, 4 females), mean age 44.0 (10.9) years. Mean follow-up 4.25 years.	HRH, Drop jump height, calf circumference, RoM, tendon length.	• Compared to the uninjured side, the participants had lower HRH maximum scores and HRH repetitions. • Lower drop jump height. • Lower calf circumference and ankle dorsiflexion RoM. • No difference in tendon length.

Table 1. *Cont.*

Authors/Years	Subjects	Variables	Findings
Bleakney et al. (2002) [36]	General population, 72 patients (58 males, 14 females), average age 49.3 years (30–82) 10–120 months (average 62.5 months); 70 matched controls.	Achilles tendon diameter, echogenicity, calcifications.	• The average maximum anteroposterior diameter of the ruptured tendon was 11.7 mm (uninjured side = 5.4 mm; controls = 4.9 mm). • 17 patients exhibited hypoechogenicity and 10 showed calcifications.
Rosso et al., 2015 [37]	General population, 52 patients (male: female ratio not stated), average age: 48.6 (8.7) years, >3 years after injury.	Isokinetic strength, active dorsiflexion RoM.	• Peak plantar flexion torque (PPFT) was significantly weaker on the injured side compared to the uninjured side (80.4 $\pm$ 29.7 Nm vs. 92.1 $\pm$ 27.4 Nm). • Active RoM was not different between the legs.

3.1. Muscle Strength and Performance

Plantar flexion strength was assessed in 11 studies, with the majority reporting deficits persisting at long-term follow-ups. For instance, Baxter et al. [16] reported a 47% deficit in the isometric strength of plantar flexors for 47% compared to a healthy leg at 2.5 years after ATR. Studies using longer follow-ups indicated that this deficit might be lower with time; Wenning et al. [19] reported a 10.2% deficit after 3.5 years, while Metz et al. [34] and Walker et al. [24] reported that there were no deficits left at 8.7 and 4.4 years after the injury, respectively. However, some studies reported persistent deficits with even longer follow-ups. Willy et al. [25] reported 4–20% deficits in concentric and eccentric strength after 6.1 years, and Horstmann et al. [7] reported 14.9% deficits in total work during isokinetic measurements after 10.8 years. Finally, Heikkinen et al. [21] reported 12–18% deficits even after 14 years. Only one study assessed strength in athletes [15] and reported that most athletes (73%) restored their strength within 3 years after the injury.

Decreased strength was reflected in the performance of various other tests. Nicholson et al. [20] reported a notable reduction (−12%) in countermovement jump height, while Willy et al. [25] suggested an 8–9% reduction in angular velocity during jumping. Several studies also used the heel-rise height (HRH) test, which is likely underpinned by strength. Notable reductions in HRH tests were noted in most studies, possibly persisting even after 10 years [7]. In summary, muscle strength is often impaired long after the ATR, which is also reflected in reduced/altered jumping and running performance, as well as local performance tests, such as HRH.

3.2. Range of Motion

Range of motion (RoM) was assessed in several studies, but rarely as a primary outcome variable. Don et al. [30] suggested that passive ankle RoM recovers within a year. Similarly, Rosso et al. [37] reported no deficits in ankle RoM after 3 years. However, in reruptured patients, Westin et al. [35] reported a 5° deficit in dorsiflexion after 4.25 years. Interestingly, Nicholson et al. [20] reported reduced internal and external hip rotation RoM. In summary, it seems that RoM may be easier to restore than strength, but patients with reruptures might be susceptible to long-term RoM deficits.

3.3. Muscle and Tendon Morphology

Studies have focused on various aspects of muscle/tendon morphology and architecture. Two studies assessed gastrocnemius fascicle lengths; Baxter et al. [16] reported 59% shorter fascicles on the injured side after 2.5 years, while Nicholson et al. [20] reported 12–20% shorter fascicle lengths after 4.4 years. Studies are also in agreement regarding the pennation angle, which seems to be increased after ATR. While Baxter et al. [16] again showed the most pronounced deficit (162%) after 2.5 years, others have reported smaller deficits with longer follow-ups [18,20,31]. Studies also reported reduced muscle thickness, volume and cross-sectional area, as well as calf circumference on the injured side during various follow-up periods [15,16,20,28,32,35]. Regarding the tendon properties, the tendon length was increased on the injured side in several studies. For instance, injured tendons were on average 1.7 cm longer after 4.5 years in the study by Kastoft et al. [33], and exactly the same value was reported after 2 years in the study by Follak et al. [32]. In addition, tendon stiffness is increased after ATR [27], while passive ankle joint stiffness recovered within 1 year in one study [30], but not within 4.5 years in the other [26].

4. Discussion

Our goal was to review research on the long-term deficits caused by an ATR injury. Our research questions focused on the extent to which and the manner in which long-term consequences may alter movement patterns, the nature of delayed changes in calf muscle composition and architecture, and whether and to what extent changes in calf muscle strength and functionality are present. The main findings suggest that ATR leaves long-term changes in the architecture of the Achilles tendon and triceps surae muscles. These include changes in Achilles tendon length and stiffness and atrophy of the triceps surae muscle. This leads to biomechanical adaptations in the kinetics and kinematics of movement. In most studies, the authors point out a major problem in ATR rehabilitation. They suggest that with the right approach, focus and more emphasis on specific goals and content during the rehabilitation itself, these long-term consequences of ATR could be reduced. This is also important to prevent other musculoskeletal structures, as compensation that occurs after ATR may put additional stress on particular structures, notably in the knee joint.

Studies have consistently found morphological and structural changes in the injured Achilles tendon. Its length remains elongated in the long term, with most studies finding an average lengthening of ~12 mm. It is hypothesised that the lengthening of the tendon is due to the altered structure of the triceps surae muscle, specifically the gastrocnemius medialis muscle [16]. All studies showed atrophy of the calf muscle. Heikkinen et al. [21] observed in their study that atrophy of the triceps surae is partially compensated by hypertrophy of the flexor hallucis longus muscle. Most studies also show increased stiffness and decreased elastic properties of the tendon. The Achilles tendon is important for energy transfer and storage, and ATR limits this transfer [19]. The one-legged heel lift test has been used in several studies. Brorsson et al. [22] examined calf muscle performance and concluded that after 7 years, the maximum heel lift improved, but only minimally, and that most improvements occurred in the first 2 years of recovery. Similarly, Brorsson et al. [8], in their second study, suggest that regaining heel elevation is important for the long-term recovery of ankle biomechanics.

Most studies also reported deficits in ankle strength and strength endurance. Walker et al. [24] noted a decreased ability to maintain the plantar flexion moment on the injured side. There was also a change in the amount of maximum ankle range of motion. Horstmann et al. [7] reported that it does not return to the level of the intact leg even after 10 years. During the execution of various jumps, in addition to a reduced ROM of the ankle, a very large deficit in plantar flexion work in the concentric phase is observed [9]. Only three studies show muscle activation or neuromuscular adaptations that are permanent. Complex neuromuscular changes occur that allow the Achilles tendon to produce maximal force while protecting it from injury.

Recent studies [31,33] reported that although the anatomy of the muscle structure of the triceps surae muscle was not restored after 4 years of ATR, the gait pattern was largely symmetrical under test conditions. Both studies concluded that the clinical significance of Achilles tendon lengthening is uncertain. Deficits in strength and range of motion may alter the kinetics and kinematics of movement, but these changes may only be detectable in more demanding movements, such as running and jumping. In these tasks, the increased load on the knee joint is of particular concern [25]. Most authors believe that these adaptations and deficits limit further athletic performance and participation. Jandacka et al. [13] point out that most individuals are at high risk for Achilles tendon and knee injuries after ATR. However, at long-term follow-up, most subjects had good subjective scores on the ATRS and PAS functional trait scores, suggesting that they had adapted to the deficits.

We also noted some limitations in the research identified and collected. In some studies, the authors themselves point to individual differences between subjects, even when treated with the same standardised protocol [20]. It is difficult to generalise based on these differences. Most studies have been conducted only on men. Little research has been conducted on athletes, making it difficult to draw conclusions about how exercise morphology and biomechanics would change in this population. The available evidence suggests that athletes sustaining ATR have impaired running kinematics and deficits in muscle morphology, while strength seems to be largely recovered [13,15]. Future studies will need to address long-term deficits in various outcomes for athletes. At this time, it seems that athletes might recover at least some aspect of their function better than the general population, yet they are not immune to some long-term deficits as well.

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