

Article

Modified Ankle Joint Neuromechanics during One-Legged Heel Raise Test after an Achilles Rupture and Its Associations with Jumping

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Featured Application: Application: It is strongly recommended that eccentric exercises involving the soleus muscle be included in supplementary treatment regimens to reduce neuromechanical compromises after an Achilles tendon rupture.

Abstract: This study had two purposes. The first purpose of the study was to compare the electromyographic (EMG) and dynamic characteristics in injured and non-injured legs during the one-legged heel-raise test after a unilateral Achilles repair. The second purpose was to determine the correlations between the EMG results and the dynamic characteristics and between the characteristics in the eccentric phase and jumping distance. Twenty-six participants who underwent an Achilles repair between 4 and 12 months prior to the measurement were recruited to perform the following bilateral tests: (1) one-legged heel-raise test with measurements of muscle activation, kinematics, and kinetics and (2) one-legged forward jumping. During the heel-raise exercise, there were increases of the EMG amplitudes in the soleus and tibialis anterior muscles, lower ankle joint angle and angular velocity, lower normalized ground reaction force, and mechanical work in the repaired legs in comparison to the non-injured legs. The EMG results of the medial gastrocnemius and soleus muscles correlated with the dynamic results ($r_s = 0.467$ and -0.537). Furthermore, the dynamic data in the eccentric phase were correlated with the jumping performance ($r_s = 0.575$ and -0.471). It is concluded the soleus muscle undergoes neuromechanical changes, including changes in EMG and dynamic characteristics, and changes affecting jumping performance.

Keywords: achilles tendon; biomechanics; muscle activation; rehabilitation

1. Introduction

Achilles tendon ruptures frequently result in long-term deficits in muscle strength and ankle functions [1–4]. Clinically, it is important to identify neuromuscular deficits in individuals who are still recovering from an Achilles rupture and to design a rehabilitation plan accordingly. Studies have validated the utility of the one-legged heel-raise (OLHR) test for measuring the morphological adaptations in the myotendinous unit, such as muscle

fascicle shortening in the medial gastrocnemius muscle and Achilles tendon lengthening, in the involved leg following an Achilles rupture [2,5–7]. The OLRH test requires the plantarflexor muscles to alternate between generating concentric force to achieve a position of maximal plantarflexion and then using eccentric control to lower the heel to a position of maximum dorsiflexion in unipedal stance [1,4]. The limb symmetry index (LSI) of average heel-rise work in the OLHR test between involved and non-involved legs one year after Achilles tendon rupture was reported to be correlated with kinetic variables during hopping, such as LSI plantarflexion power (force times velocity), six years after the injury [1]. This indicates that the musculotendinous factors that affect the performance of the OLRH test one year after a rupture may also affect common functional activities, such as hopping, later on in injured legs. Another study demonstrating electromyographic (EMG) activity in the OLHR test for all of the triceps surae muscles found that the muscles have similar EMG results during the concentric phase of the OLHR test with reduced heights of heel lifting for the involved side compared to the uninvolved side [8]. However, neither the EMG activities of individual tricep surae muscles, nor the kinetics and kinematics data for the eccentric phase, were analyzed in that study.

The eccentric phase of the OLHR test may potentiate force production for ankle plantarflexion, which has been reported in previous studies involving stretch-shortening cycle (SSC) trials [9]. Various possible mechanisms underlying force enhancement in the eccentric phase of the SSC have been proposed, including mechanisms involving the joint angle (force-length relationship of muscle) [10], angular velocity (reflex potentiation) [11], magnitude of stored elastic energy, and the applied force that induces elongation of the myotendinous complex [9]. In previous studies that examined muscle atrophy (i.e., the side demonstrating muscle atrophy) in the medial gastrocnemius and soleus muscles of patients with an Achilles tendon rupture, the morphological findings have shown that the muscle activation of these muscles may be accompanied by atrophy that may in turn affect dynamic variables during the OLHR test [12–14]. However, this hypothesis has not been proven. The depiction of the dynamic (kinetic and kinematic) profile of the OLHR test and the muscle activation involved following an Achilles rupture can best explain the neuromechanical mechanisms leading to performance deficits in the OLHR test and, therefore, further studies are required.

The aim of the present study was two-fold. First, the study utilized the OLHR test to assess and compare the EMG, kinematic and kinetic characteristics in the injured and non-injured legs of participants within one year of a unilateral Achilles' repair. Second, the study aimed to determine the relationship between (1) the EMG results of calf muscles (including the medial gastrocnemius and soleus) and the kinetic and kinematic characteristics and (2) those characteristics and normalized jumping distance. We hypothesized that, firstly, when compared to their contralateral non-injured legs, the repaired legs of the participants with an Achilles repair would exhibit compensatory increases of EMG activity in the leg muscles and correlated with lower values in terms of the kinematics and kinetics characteristics. Secondly, that these biomechanical characteristics would be correlated with the normalized distance of one-legged jumping.

2. Materials and Methods

This study focused on the neuromechanical deficits in OLHR tests and, therefore, recruited only patients who were recovering from an Achilles tendon rupture sustained within the last 12 months (no physically-matched uninjured participants were recruited as controls) [5]. This study was approved by the institutional review boards of National Taiwan University Hospital (reference no. 201507028RINC) and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Written informed consent was obtained from all the participants prior to their participation. Six orthopedic surgeons who primarily use the Kessler suturing technique to repair ruptured Achilles' tendons and that recommend a 16-week rehabilitation protocol [5,15] after such repairs were recruited for the study for subject recruitment. The inclusion criteria required

the participants to have suffered from a unilateral Achilles' tendon rupture and surgical management, to be aged between 20 and 60 years old, and to have undergone the repair surgery within the past four to twelve months. Potential participants were excluded if they: (1) exhibited any positive signs or evidence of tendinopathy in their non-injured control leg as determined by physical examination [16] or ultrasonographic screening [17] with a 4–15 MHz broadband linear array transducer (T3300, BenQ, Taoyuan, Taiwan); (2) had a delayed surgery (>1 week) or were diagnosed with a sural nerve injury; or (3) did not complete the 16-week rehabilitation protocol with physiotherapists [15]. Measurements were taken for both legs (that is, the repaired leg and non-injured leg) of all the participants in the order of a block randomization scheme. There was a 10-min interval of rest between the measurements for the two legs.

2.1. Participants

Based on our pilot work with participants with an Achilles' repair and based on a value of 0.05 for alpha (α) and a power of 0.80 for the statistical test, the minimum sample size required for significant differences between repaired and non-injured legs for the soleus EMG activity in maximal heel lifting was 25. Twenty-six participants with a unilateral Achilles' tendon repair were recruited, and their characteristics are shown in Table 1. None of the potential participants required exclusion. Their Lower Extremity Functional Scale (LEFS) scores indicated moderate to high functional levels (Table 1).

Table 1. Characteristics [reported as means (interquartile range)] and self-reported functional levels of the participants with an Achilles rupture ($n = 26$).

Characteristics	Achilles Repair
Age (y)	40.5 (19.5)
Gender (n): Male/Female	21/5
Repaired leg (n): Right/Left	15/11
Body height (cm)	173.6 (7.0)
Post-surgery period (months)	4.5 (5.15)
Body weight (kg)	74.8 (12.5)
Injury mechanism (n): Sports/Non-sports injury	24/2
LEFS score	75 (6.5)

Abbreviations: LEFS, Lower Extremity Functional Scale; NA, not available. Age, body weight, body height, and post-operation history and questionnaire scores are presented as median values, with the interquartile range in the parentheses.

2.2. Isometric EMG Measurement

The methods of isometric EMG measurement have been described in a previous study [6]. Briefly, each participant lay prone (face down) on an examination bed with both ankles hanging over the edge [6]. The foot was fixed on the footplate, which was placed at a 90° angle to the tibia. A load cell (SLS410 Load Cell, Mettler-Toledo PacRim AG, Taiwan) connected to a footplate and an MP100 system (BIOPAC System-Inc, Santa Barbara, CA, USA) and sampled at 1200 Hz was then used to record voluntary isometric torque. The myoelectrical activities of the gastrocnemius medialis, gastrocnemius lateralis, soleus, and tibialis anterior muscles were measured using wireless surface EMG recording electrodes (DTS, myoRESEARCH™3.8.6, Noraxon, Scottsdale, AZ, USA) sampled at 1500 Hz. Each participant was instructed to gradually increase the plantarflexion and dorsiflexion forces in their foot from a relaxed status to the maximal voluntary isometric contraction (MVIC) and maintain the MVIC for 1 s. Visual feedback indicating the exerted plantarflexion and dorsiflexion forces was given to the participants in order to help ensure consistent performance. All measurements were averaged over at least three trials. For synchronization, software containing simulating switching circuits written

using LabVIEW7.1 (National Instruments, Austin, TX, USA) was used to add electrical signals to the EMG and MP100 system at the beginning and end of each measurement. The amplitudes of the root mean square (RMS) EMG during plantarflexion and dorsiflexion quantified for 1.0-s epochs and corresponding to the plateau levels of plantarflexion and dorsiflexion MVIC were used to normalize subsequent EMG data series gathered in the concentric and eccentric phases of the exercises [18,19].

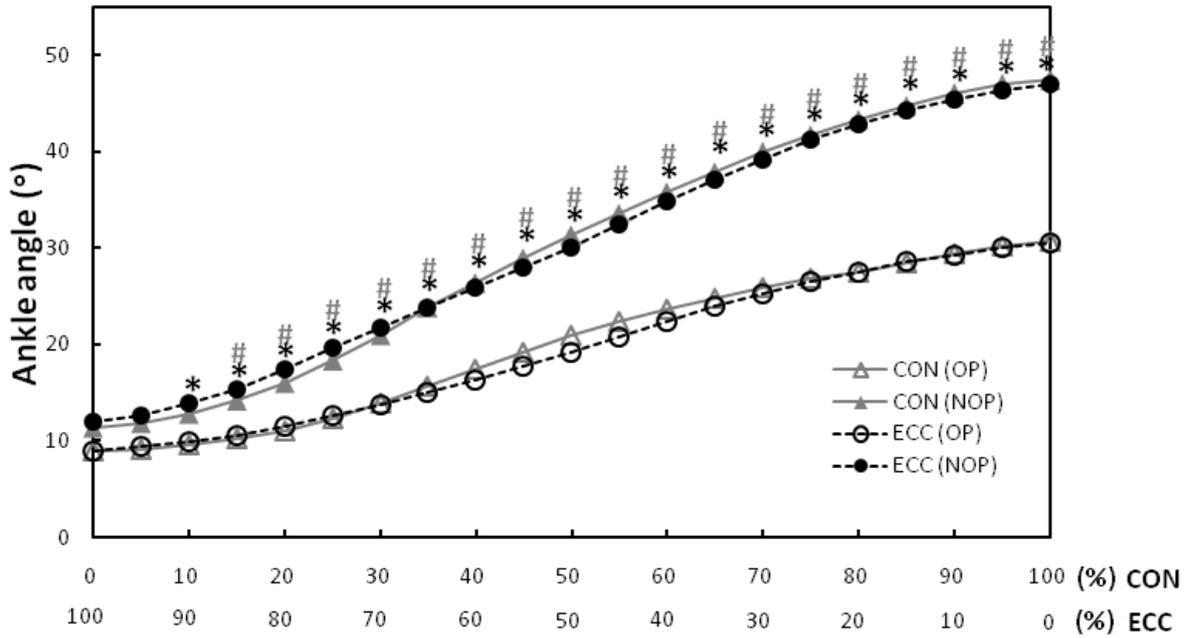
2.3. EMG, Kinematic and Kinetic Data during Heel-Raise Exercise

The measurements were performed with a Noraxon myoSYNC™ synchronization system synchronized with a full HD and infrared-camera (30 Hz, 138-2, Noraxon, Scottsdale, AZ, USA) integrated video analysis system (Noraxon, Scottsdale, AZ, USA) and a 60 × 50 cm force platform (9260AA, Kistler Group, Winterthur, Switzerland) connected to the MP100 system. The locations of the reflective markers used in ankle kinematics analyses have been described in a previous study [6]. They were placed and fixed on the upper part of the posterior calcaneal tuberosity, lateral aspect of the 5th metatarsal head, lateral malleolus, fibular head, femoral epicondyle, and thigh at 50% of the distance between the greater trochanter of the femur and the lateral tibiofemoral joint line of the tested leg of each participant [6,20] (Figure 1). The positions of the markers were used to calculate the sagittal plane knee and ankle joint angles. For example, the 0-degree or neutral position of the ankle is determined by a 90-degree angle between the fifth metatarsal and the fibula. Each participant stood on his or her single tested leg with the forefoot positioned in the middle of the edge of the step to allow full dorsiflexion to be reached (Figure 1). The given participant was allowed to touch the wall with an index finger at the shoulder level to maintain a steady one-leg standing position. The participant was then instructed to perform two sets of exercise tasks, with each set consisting of three cycles of full-weight-bearing ankle concentric (raising the heel to the peak ankle plantarflexion angle) and eccentric (lowering to the peak ankle dorsiflexion angle) exercises, with the participant's weight borne on the knee at a 0° extension, without loss of balance. The pace of the ankle movements was guided by a metronome set at 60 beats per minute giving four beats for a full cycle of plantarflexion and dorsiflexion. The concentric and eccentric phases were identified from the sagittal ankle joint angles through a video analysis system that determined, respectively, the elapsed time of dorsiflexion (flexion at the ankle, so that the foot points more superiorly) and plantarflexion (extension at the ankle, so that the foot points inferiorly). The simultaneous EMG, kinematic and kinetic recordings were averaged among the second and third consecutive cycles in each of the two exercise sets. The recordings were discarded and the measurement restarted if the given participant could not keep pace with the metronome, keep his or her trunk and knee straight (knee flexion 0–5 degrees as shown in the video analysis system), or if he or she lost his/her balance.

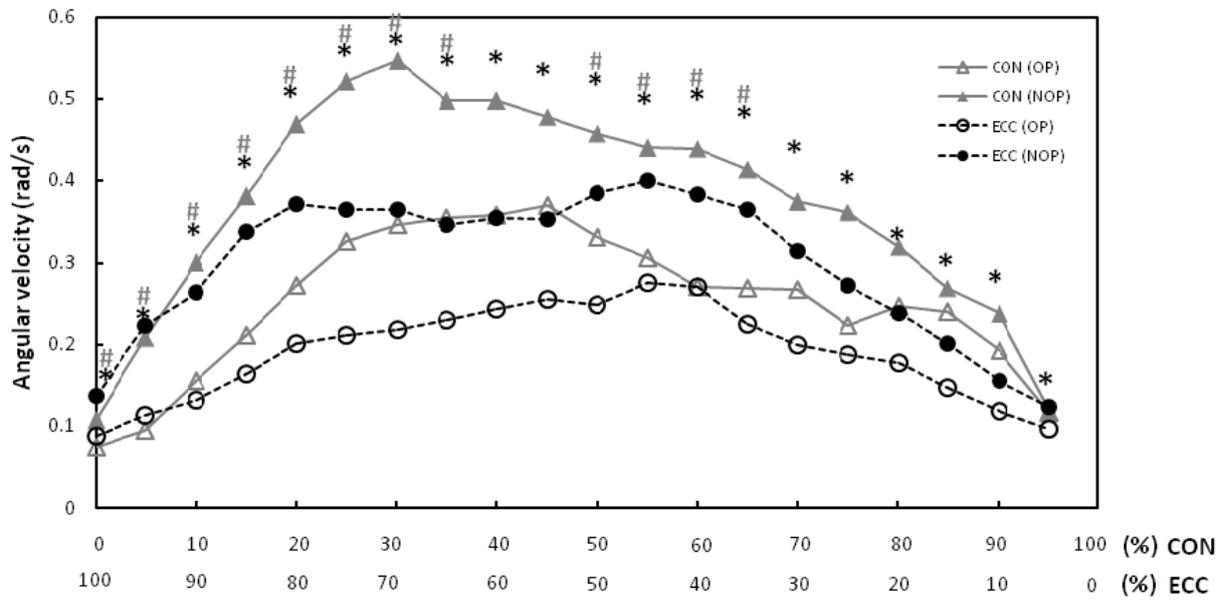


Figure 1. The experimental setting comprising the electromyographic (EMG) recording electrodes, marker set, and force plate used for motion analysis.

The analyses included analyses of the RMS EMG amplitudes of the muscles, the RMS amplitudes of the ground reaction force (GRF), and mechanical work of heel lifting, all of which were quantified corresponding to the concentric and eccentric phases in the second and third full movement cycles. The mechanical work of the heel lifting was defined as the amplitude of the GRF in the z -axis multiplied by the lifting distance. The EMG signals were amplified (gain =500, CMRR > 100 dB) and filtered with bandwidths of 10–500 Hz. Furthermore, only the vertical component (F_z) of the GRF (determined using a 4th order Butterworth low-pass filter with a cutoff frequency of 5 Hz) normalized with respect to body weight was utilized for kinetic analysis. The RMS EMG amplitudes (mV) of the muscles were averaged and normalized based on the value measured during the MVIC. The kinematics and kinetics data including the ankle joint angle, angular velocity, normalized GRF and the mechanical work were recorded and compared for the injured and non-injured legs at every relative 5 percentage points of the duration of the concentric and eccentric phases of the exercise cycle after time normalization (linear length normalization) (Figure 2a–d). The kinematics and kinetics data, from 0 to 100%, in the concentric and eccentric phases were individually averaged for the correlation tests.



(a)



(b)

Figure 2. Cont.

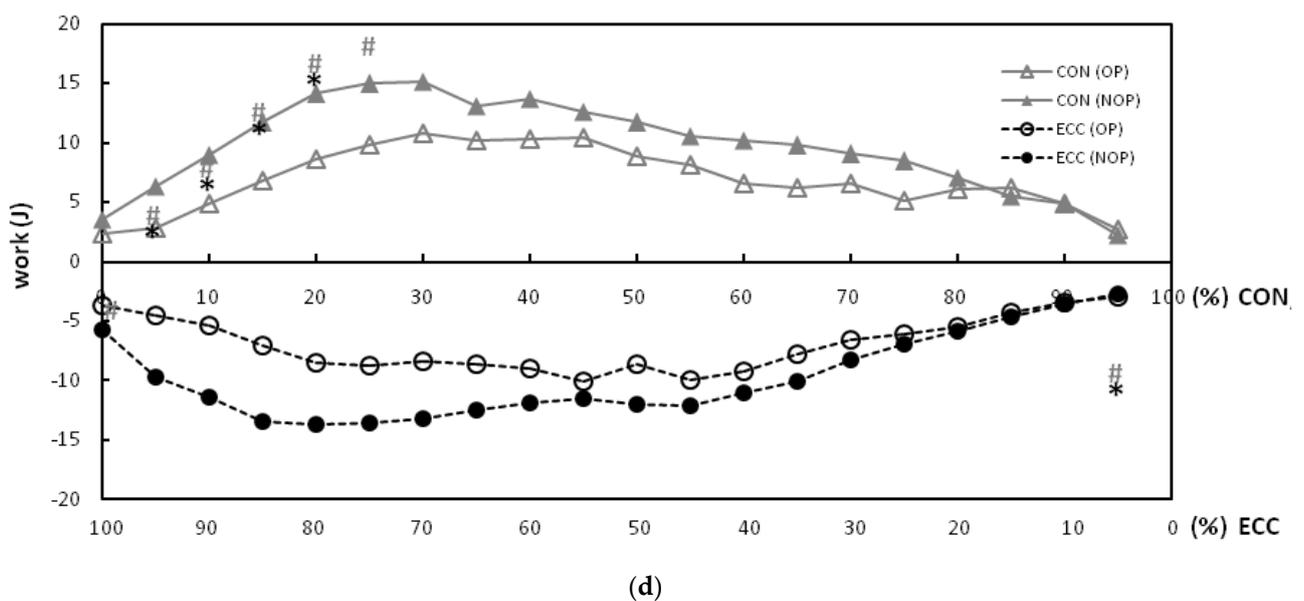
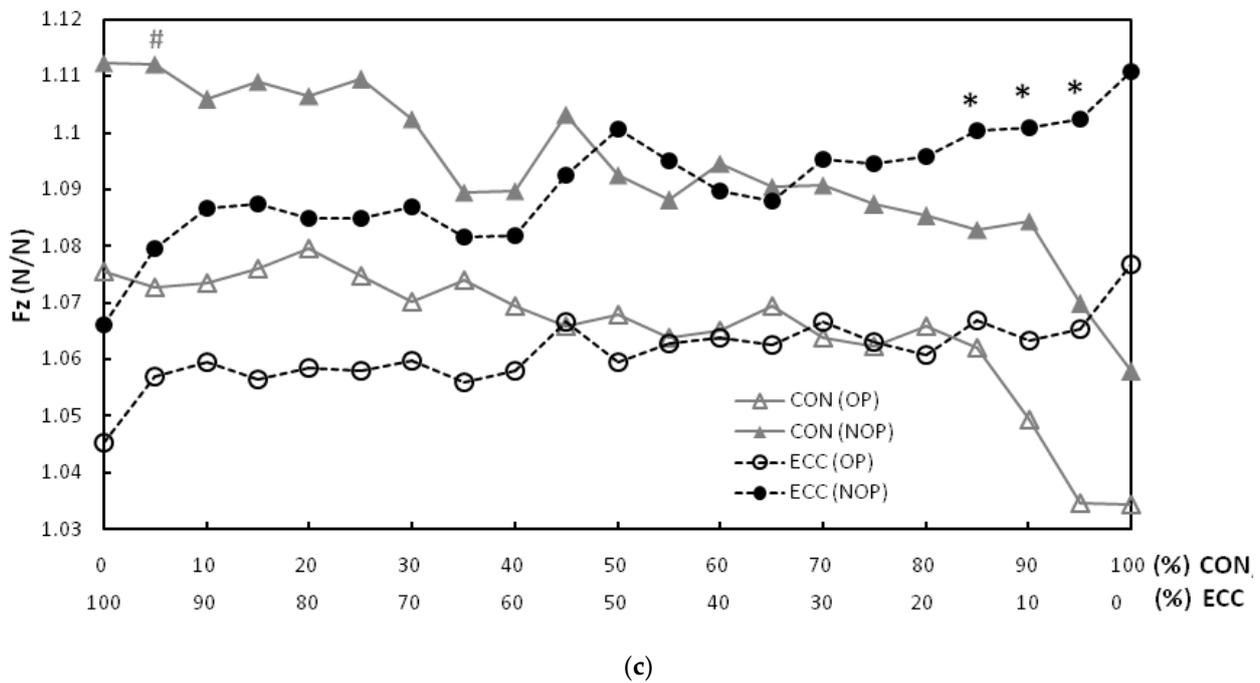


Figure 2. Records of the measured parameters ((a); ankle joint angle, (b); angular velocity of the ankle joint, (c); vertical ground reaction force normalized with respect to body weight, (d); mechanical work) were analyzed over time scale intervals of 5 percent of the normalized time of the concentric and eccentric phases, from 0 to 100%. The significant differences in the concentric and eccentric phases are marked with # and *, respectively. The p 's values in (a) ranged between 0.145 and <0.001 for # and between 0.075 and <0.001 for *; the p 's values in (b) ranged between 0.687 and 0.001 for # and between 0.07 and <0.001 for *; the p 's values in (c) ranged between 0.836 and 0.049 for # and between 0.959 and 0.026 for *; and the p 's values in (d) ranged between 0.836 and 0.002 for # and between 0.959 and 0.001 for *.

2.4. One-Legged Jumping Test

After another 10 min of rest, the patients stood behind a take-off line marked on the floor with previously described subject positioning. The participant was instructed to jump as far as possible by pushing off with one foot without losing his or her balance or placing the other foot on the ground. The participant was allowed to maximize their forward drive by performing a countermovement consisting of a quick bending of the knee and a

backward arm swing prior to the jump. Each participant performed at least three maximal trials for each leg, with the longest jumping distance for each leg recorded and normalized to body height for analysis.

2.5. Self-Reported Questionnaire

After the biomechanical measurements, each participant indicated the functional level of his or her lower extremities by filling out the Taiwan Chinese version of the Lower Extremity Functional Scale (LEFS-TC) questionnaire [21].

2.6. Statistical Analyses

Because of a lack of normality in the data including the RMS EMG, ankle angle and angular velocity, ground reaction force and mechanical work (Kolmogorov–Smirnov test for normality, $p < 0.05$), the Wilcoxon signed rank test with the alpha level set at 0.05 was used to analyze the differences in EMG, kinematic and kinetic data between the repaired legs and non-injured legs. EMG, kinematic and kinetic data were either compared in the concentric and eccentric phases or at different times normalized to a relative percentage of the duration of the phases, from 0 to 100%. The Spearman rank correlation coefficients were calculated to determine (1) the correlations between the RMS EMG amplitudes and the dynamic (kinematic and kinetic) characteristics and (2) whether the kinematic and kinetic data in the eccentric phase were correlated with the jumping performance using the Bonferroni approach and the corrected p -value 0.01. The data were analyzed using the IBM Statistical Package for Social Sciences Statistics, version 22.0 (IBM Inc, Armonk, NY, USA).

3. Results

During the concentric and eccentric phases of the heel-raise exercise, there were increases of the RMS EMG amplitudes in the soleus and tibialis anterior muscles (Table 2, p 's ranged between 0.043 and 0.002), lower ankle joint angle (p 's ranged between 0.145 and <0.001), angular velocity of the ankle joint (p 's ranged between 0.687 and <0.001), normalized GRF (p 's ranged between 0.959 and 0.026) and mechanical work (p 's ranged between 0.959 and 0.001) in the repaired legs when compared to ones of the non-injured legs (Figure 2a–d). The EMG results of the medial gastrocnemius and soleus muscles were correlated with the kinematics or kinetics results ($r_s = 0.490$ and -0.560) (Table 3). Furthermore, the joint angular velocity and mechanical work data in the eccentric phase were correlated with the normalized jumping performance ($r_s = 0.575$ and -0.471) (Table 4).

Table 2. Results of normalized RMS EMG data during the concentric and eccentric phases of the one-legged heel-raise exercise, and normalized hopping distance.

RMS EMG		Repaired Leg	Non-Injured Leg	p Value
TA	CON	0.20 (0.10–0.55)	0.16 (0.05–0.36)	0.027 *
	ECC	0.13 (0.07–0.48)	0.12 (0.04–0.32)	0.049 *
SOL	CON	0.99 (0.55–1.53)	0.86 (0.48–2.45)	0.023 *
	ECC	0.75 (0.31–1.28)	0.49 (0.34–1.13)	0.002 *
MG	CON	0.95 (0.59–1.37)	0.89 (0.47–1.47)	0.351
	ECC	0.64 (0.45–0.95)	0.54 (0.28–1.06)	0.204
LG	CON	0.87 (0.43–1.25)	0.91 (0.48–1.51)	0.647
	ECC	0.57 (0.29–0.86)	0.54 (0.35–0.93)	0.744
nOLH (%)		0.75 (0.40–1.01)	0.95 (0.68–1.10)	<0.001 *

Abbreviations: RMS EMG, root mean square electromyography; CON, concentric; ECC, eccentric; TA, tibialis anterior; SOL, soleus; MG, gastrocnemius medialis; LG, gastrocnemius lateralis; nOLH, normalized one-legged hopping distance. Results are presented as median values, with the range between the minimum and maximum for each value in parentheses. * means significant difference.

Table 3. Spearman rank correlation coefficients between the EMG results of four leg muscles and the kinetic and kinematic characteristics during the one-legged heel-raise exercise.

CON phase	Kinematic		Kinetic	
	Ankle joint (°)	Joint angular velocity (rad/s)	Normalized ground reaction force Fz	Mechanical work (J)
Sol RMS EMG	−0.011 (0.952)	−0.072 (0.684)	−0.404 (0.021)	−0.327 (0.056)
MG RMS EMG	0.490 * (0.004)	−0.065 (0.726)	−0.041 (0.812)	0.040 (0.948)
ECC phase				
Sol RMS EMG	0.013s (0.959)	−0.281 (0.113)	−0.153 (0.417)	−0.560 * (0.001)
MG RMS EMG	0.247 (0.180)	−0.199 (0.276)	0.058 (0.751)	−0.127 (0.490)

Abbreviations: RMS EMG, root mean square electromyography; CON, concentric; ECC, eccentric; TA, tibialis anterior; SOL, soleus; MG, gastrocnemius medialis; LG, gastrocnemius lateralis. Correlations are presented as r_s values, with the associated p values in parentheses. * means significant.

Table 4. Correlations between the kinematic and kinetic characteristics (in the eccentric phase of the one-legged heel-raise exercise) and normalized one-legged hopping distance.

Kinematic and Kinetic Data	Spearman Rank Correlation Coefficients
Ankle joint (°)	−0.192 (0.293)
Joint angular velocity (rad/s)	0.575 (0.001) *
Ground reaction force Fz (n)	−0.077 (0.675)
Mechanical work (J)	−0.471 (0.007) *

The Spearman correlation coefficients are presented as r_s values, with the associated p values in parentheses. * means significant.

4. Discussion

This study first depicted the altered muscle activation, including the kinetic and kinematic characteristics, in repaired legs with an Achilles tendon rupture. Secondly, it confirmed our hypothesis regarding differences in neuromuscular recruitment strategies in the ankle joint between the involved and non-involved legs when performing the OLHR test in participants who are still recovering from an Achilles tendon rupture. The correlation results demonstrated that the muscle activations in the medial gastrocnemius and soleus muscles were respectively associated with the total ankle angle in the concentric phase and the negative work in the eccentric phase of the OLHR test. Furthermore, the kinematic and kinetic characteristics in the eccentric phase were correlated with the jumping performance. These observations indicated that the soleus muscle is involved in the compromised muscle force production and the storage of elastic potential energy and may affect the jumping performance in patients who have undergone a repair surgery within the past year. These observations suggest the advisability of supplementary muscle-specific rehabilitation for an Achilles tendon rupture in order to promote functional recovery.

The comparisons between the repaired and non-injured leg groups showed that the repaired legs exhibited augmented muscle activation in the soleus and tibialis anterior muscles during the concentric and eccentric contractions (Table 2). This high antagonist EMG activity may result from alterations of the neuromotor links between joint mechanoreceptors and antagonists [22,23]. Furthermore, reductions in the mechanical properties of the medial gastrocnemius muscle with shortened fascicles, as well as the lengthening of the Achilles tendon with low stiffness [6,18], may also trigger the greater recruitment of the soleus muscle found in this study, which in turn augments the tibialis anterior muscle coactivation, in the legs with an Achilles rupture [24]. This augmented co-activation may result in decreases in kinematic and kinetic performance and characteristics (Figure 2a–d) in injured legs, including in the net joint force or GRF, during the OLHR test, although it

may be beneficial to ankle joint stability [25]. Such augmented co-activation in a repaired leg is consistent with that identified in a study involving bilateral hopping performed by patients years after the surgical repair of a torn Achilles [26]. This implies that such augmented coactivation, which jeopardizes ankle plantarflexion torque production, may be observed through the early to late stages of rehabilitation if early physiotherapy after the Achilles tendon rupture does not include soleus muscle training. Explosive strength training and eccentric resistance training have been shown to efficiently suppress the antagonist muscles and increase the maximal voluntary torque of the plantar-flexor muscles [27,28]. Eccentric resistance training was additionally found to increase the muscle fascicle with increasing magnitude [29], which may be beneficial for reducing the muscle fascicle shortening that occurs as part of the gastrocnemius muscle atrophy seen after an Achilles tendon rupture [6]. The results of this part of the current study indicate the advisability of incorporating supplementary eccentric strengthening of the plantarflexor muscles into the rehabilitation after an Achilles rupture in order to reduce antagonist co-activation and enhance the plantarflexion torque.

Our results further demonstrated that there are associations between the muscle activation of the medial gastrocnemius and the ankle joint in the concentric phase, and that soleus EMG activity is associated with high negative mechanical energy in the eccentric phase of the OLHR test. These correlations indicated the muscular contributions to the kinematic and kinetic characteristics during the OLHR test. Suydam et al. observed increased EMG activities in the medial gastrocnemius muscle during walking in patients with an Achilles rupture and declared these increased activities to be caused by tendon lengthening [30]. It is possible that the correlation found in the medial gastrocnemius muscle reflects its architecturally largest angulations of the fascicles, which favor force production [31], even though muscle fascicle shortening in the medial gastrocnemius muscle and Achilles tendon lengthening occur in the involved legs. The soleus EMG activity associated with negative mechanical energy during eccentric contractions implies a dependence of elastic energy storage on the soleus muscle that is accomplished through increases of muscle activity after an Achilles rupture. This assumption could be supported by the observation that when the plantarflexion angle is increasing with extra loading during eccentric contractions, the soleus muscle is more affected than the gastrocnemius muscle in terms of increases in EMG activity [24]. Collectively, these correlations support the possible contributions of the above muscles during the OLHR test and suggest that the enhancement of soleus muscle activation may be effective in terms of energy storage and enhancing movement efficiency, and the eccentric strengthening of the soleus could prevent excessive mechanical energy from being dissipated by the Achilles tendon and, thereby, reduce the risk of re-rupture. Our findings in this regard underscore the need to carry out eccentric exercises for late-stage rehabilitation. It is suggested, relatedly, that future studies be conducted to assess the training effects of soleus eccentric exercises on the maximal and explosive ankle performances in participants soon after an Achilles rupture in order to verify the role of the soleus muscle in functional recovery.

The kinematics and kinetics data in this study showed that, in a repaired leg, there are reduced amplitudes in the ankle joint angle, angular velocity, ground reaction force and mechanical work of the heel during the concentric and/or eccentric phases in the OLHR exercise (Figure 2a–d). These parameters in the concentric and eccentric phases respectively represent various aspects of performance, including force and movement generation, as well as factors of force potentiation induced by the SSC, including muscle length (ankle joint), rate of length change or reflex potentiation (angular velocity), force applied and induced joint angular movement or tissue deformation (ground reaction force), and stored elastic energy (negative works) [10,11]. Throughout the concentric and eccentric phases, the kinematics data, respectively, demonstrated that the repaired legs exhibited less angular movement generation and velocity, and that a poor length-force relationship and reflex potentiation reduced ankle joint angles (Figure 2a,b). Since the fascicle of the medial gastrocnemius muscle is respectively shortened and stretched as the foot is perform-

ing concentric and eccentric plantarflexion contractions [6,32,33], our kinematics results indicated that fascicle contraction or the contributions of the fascicles and aponeurosis to the muscle-tendon unit shortening velocity in the repaired legs were reduced within the end range of plantarflexion motion. Furthermore, the Achilles tendon lengthening that occurs after a rupture may adversely affect the tendon elongation magnitude within the end range of plantarflexion motion [8] and, therefore, decrease the operating range or velocity of the fascicle simultaneously. Our results regarding the reduced ground reaction force and mechanical work done during the concentric and eccentric phases in the repaired legs could also be illustrated by the above-assumed mechanism (Figure 2c,d). However, the kinetic data only showed significant differences in either the beginning or end of the phases, unlike the kinematic data, which showed differences throughout the phases. Our correlation data also showed that there were correlations of the kinematic (ankle angular velocity) and kinetic (mechanical work) results in the eccentric phase with the normalized distance results of the one-legged jumping test ($r=0.575$, and -0.471 , respectively). These findings are comparable to those of a previous study using a linear encoder that showed that the heel position-derived parameters during heel-raise exercises correlated with ankle kinematics during walking [1]. This study with three-dimensional kinematic and kinetic analyses further pointed out that, during the OLHR test, the mechanical work done by the plantarflexor muscles could be a predictor of jumping performance. Clinicians and therapists may enroll this parameter without actually measuring jumping performance with risks from high-magnitude impact forces or falls. However, we cannot rule out the possibility that the correlation observed in this study is due to the reduction in the ankle range of motion or the calf muscle flexibility affecting the one-legged heel raise or jumping performance [34–37]. This is because previous studies have shown that insufficient mobility or flexibility of the ankle can impair vertical jump ability [34–37]. Since jumping for distance is important in sports, future studies are encouraged to assess the kinetic characteristics and to investigate the associations between those characteristics and the time required to reestablish the ability to participate in sports after an Achilles rupture.

The limitations of this study include its retrospective study design and the specific population that was studied. The current study utilized a side-to-side comparison to measure adaptation in morphomechanical properties following an Achilles' rupture. Therefore, care must be taken in interpreting results when using the non-injured leg as the reference because the adaptations in the non-injured legs may also be postoperative time- and recovery-dependent. Furthermore, kinematic characteristics, such as the angular velocity and peak dorsiflexion angle in the OLHR exercise, appear to depend on the frequency and the use of a pedestal [38]. Therefore, our results may be not applicable to other exercises involving different frequencies or the use of a pedestal. Lastly, the absence of information for muscle co-activation during OLHR testing and regression analysis to correlate OLHR biomechanics, as well as jumping performance, should be seen as limitations related to methodology in this study.

5. Conclusions

The results of this study support the conclusions that a leg with a repaired Achilles tendon rupture exhibits neuromechanical changes including changes to EMG and dynamic profiles, and that the dynamics of the ankle joint during eccentric contraction are associated with jumping performance. This study indicated that the previously reported muscle atrophy in the patients with an Achilles tendon rupture led to an alteration in the muscle activation of the leg muscles and in turn affected dynamic variables during the OLHR test. It is suggested, relatedly, that future studies be conducted to assess the training effects of plantarflexion eccentric exercises on functional recovery in participants years after an Achilles rupture.

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