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DETERMINANTES PARA O TESTE FUNCIONAL DE ELEVAÇÃO DO CALCANHAR APÓS DOIS ANOS DE RUPTURA DO TENDÃO DE AQUILES

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Trabalho de conclusão de curso entregue ao curso de fisioterapia da Universidade Federal do Rio Grande do Sul, sendo requisito para obtenção do título de bacharel em fisioterapia.

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RESUMO

Introdução: Após um longo período da ruptura do tendão de Aquiles (RTA), déficits funcionais ainda são encontrados. No entanto, não se tem conhecimento de quais variáveis estão mais relacionadas com estas perdas. **Objetivo:** Verificar a existência de déficits funcionais e quais variáveis neuromusculares e tendíneas melhor explicam os resultados de um teste funcional de elevação do calcanhar (TFEC) após dois anos do reparo cirúrgico do tendão de Aquiles. **Metodologia:** Trinta sujeitos foram divididos, inicialmente, em três grupos: controle (N=10 sujeitos), tradicional (N=10 sujeitos) e acelerado (N=10 sujeitos); e posteriormente realocados nos grupos: saudável (SAU; N=20 membros), não afetado (NA; N= 20 membros) e afetado (AF; N= 20 membros). Foram mensurados: TFEC; amplitude de movimento de tornozelo; torque; ativação muscular do gastrocnêmio medial (EMG-GM) e do sóleo; área de secção transversa (AST), comprimento e módulo de Young do tendão de Aquiles e comprimento de fascículo, ângulo de penação e espessura muscular do gastrocnêmio medial. **Resultados:** Foi encontrado déficit funcional tanto nos membros que sofreram RTA quanto nos contralaterais, sendo os primeiros mais comprometidos. A AST e o torque explicam significativamente o TFEC para o grupo SAU (p=0,005). Já para o grupo NA, a EMG-GM foi a única variável que apresentou relação significativa com o TFEC (p=0,013), enquanto no grupo AF, nenhuma variável foi aceita no modelo de regressão linear. **Conclusão:** À longo prazo os pacientes ainda apresentam déficits funcionais e nenhuma das variáveis pode explicar o desempenho do TFEC para os membros que sofreram RTA.

Palavras-chave: calcâneo, lesões do tornozelo, protocolos clínicos, reabilitação, ruptura, tendão de Aquiles.

ABSTRACT

Introduction: After a long period of rupture of the Achilles tendon (RAT), functional deficits are still found. However, it is not known which variables are most related to these losses. **Objective:** To verify if there are functional deficits and which neuromuscular and tendinous variables better explain the results of a heel elevation functional test (HETF) after more than two years of the surgical repair of the Achilles tendon. **Methodology:** Quantitative study, with 30 subjects, divided into three groups: control (N = 10 subjects), traditional (N = 10 subjects) and accelerated (N = 10 subjects); subsequently divided into: healthy (HEA, N = 20 members), unaffected (UNA, N = 20 members) and affected (AFF; N = 20 members). The following variables were measured: HETF, ankle joint range of motion, torque, medial gastrocnemius (MG-EMG) and soleus activation, Achilles tendon length, cross-sectional area (CSA) and Young's modulus, fascicle length, pennation angle, muscle thickness of the medial gastrocnemius. **Results:** Functional deficit was found both in the limbs that suffered RTA and in the contralateral ones, being the first more compromised. AST and torque have a significant relationship with the HETF for the HEA group ($p = 0.005$). For the UNA group, the MG-EMG was the only variable that presented a significant relationship with the HETF ($p = 0.013$), while in the AFF group, no variables were accepted in the linear regression model. **Conclusion:** In the long run, patients still present functional deficits and none of the variables can explain the performance at the HETF for the patients who suffered RTA.

Keywords: Calcaneus, ankle injuries, clinical protocols, rehabilitation, rupture, Achilles tendon.

SUMÁRIO

APRESENTAÇÃO

Este trabalho foi idealizado a partir da minha vivencia no grupo GPBIC, onde estive envolvida com projetos relacionados as propriedades do tendão de Aquiles e participando dos processos de coleta e análise de dados. Com a necessidade de entender mais sobre o assunto, a literatura me fez perceber que a fisioterapia ainda não apresenta respaldo científico claro no que diz respeito à reabilitação de indivíduos que sofrem ruptura do tendão de Aquiles. Na grande maioria das vezes, a fisioterapia não apresenta os resultados desejados após tratar esta afecção, sendo que o paciente não retorna ao estado de saúde anterior à ruptura, tendo sua funcionalidade, mesmo após um longo prazo, afetada por tal situação.

A partir destas percepções, juntamente com meu orientador, pensamos em desenvolver um trabalho que nos mostrasse se os indivíduos realmente permanecem com déficits funcionais após um longo prazo da ruptura do tendão de Aquiles e que também explicitasse com mais clareza quais são as variáveis que estão comprometidas nestes indivíduos. A partir destas respostas, a fisioterapia pode ter mais subsídios científicos para elaborar e aplicar protocolos eficazes, que promovam maior qualidade de vida para seus pacientes através da recuperação da função perdida.

Os dados analisados foram coletados após 2 anos da ruptura do tendão de Aquiles, para que fosse possível verificarmos os efeitos da ruptura à longo prazo. Este processo foi possível porque os indivíduos já haviam participado de um estudo guarda-chuva deste grupo de pesquisa, que estudou as propriedades em questão à curto prazo, logo após a ruptura do tendão de Aquiles, aplicando também diferentes protocolos de reabilitação.

A revista Clinical Rehabilitation, com fator de impacto 2.403, que abrange os campos da deficiência e reabilitação e proporciona a divulgação internacional do estudo foi escolhida para sua futura publicação, e, por este motivo, o trabalho se encontra nas devidas normas (vide anexo).

Determinants for the heel elevation functional test two years after Achilles tendon surgical repair

Original Article

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Abstract

Objectives: Verify possible functional deficits and determine which neuromuscular variables had better explained the heel elevation height two years after the Achilles tendon surgical repair.

Design: Predictive ex-post facto study; 30 male subjects divided into three groups.

Setting: Exercise Research Laboratory, Porto Alegre, Brazil.

Subjects: 30 men, 44.3 years of age; total Achilles tendon rupture and surgical repair for more than two years (n=20).

Intervention: Traditional rehabilitation program post-surgery (n=10, 6-week plaster cast immobilization, home-based exercise program), accelerated early mobilization program (n=10, 6-week exercise program for range of motion gain, twice-a-week, removable cast), healthy subjects (n=10). Structural, mechanical and functional tests were applied bilaterally. Limbs were divided into affected (AFF), unaffected (UNA) and healthy (HEA).

Main measures: heel elevation functional test, ankle joint range of motion, torque, medial gastrocnemius and soleus activation, Achilles tendon length and cross-sectional area, Young's module, fascicle length, pennation angle, muscle thickness.

Results: Higher functional deficit at the AFF compared to the UNA limb. Multiple linear regression indicated that: (1) tendon cross-sectional area and plantiflexor torque of the HEA limbs and (2) medial gastrocnemius activation of the UNA limb have a significant relation ($p=0.005$ and $p=0.013$, respectively) with the heel rising functional test. No variable was able to explain the functional test performance at the AFF limb.

Conclusions: More than two years after Achilles tendon surgical repair, patients still present functional deficits at both AFF and UNA limbs. None of the structural, mechanical and functional variables could explain the heel rise functional test performance for the AFF limbs.

Keywords

Calcaneus, Achilles tendon rupture, rehabilitation, surgical repair, heel rise functional test.

Introduction

The incidence of Achilles tendon rupture has increased in the last few years due to the increased participation in sports activities of the general population.[1-2] This injury is more common in male subjects between the third and fourth life decade, and in activities involving accelerations and sudden jumps.[3-2]

Surgical treatment is usual for the tendon repair, traditionally followed by ankle immobilization by plaster cast.[4] Despite the benefits such as protection and tissue re-rupture at the early healing phase, immobilization leads to severe muscular, neural and tendon loss, with a reduction in the capacity of the muscle-tendon unit to generate and transmit forces.[5-6-7-8]

To minimize these immobilization deleterious effects some studies have implemented early mobilization and weight bearing in addition to different immobilization techniques post-surgery.[9-4-10] However, there is no well-established protocol and the long-term results are still scarce at the literature.[4-11-8]

In addition, studies have shown that, even after a long period of the surgical repair, immobilization and rehabilitation, muscle-tendon structural and functional deficits persist in these patients.[12-13-14-15-8-16]

Therefore, it is important to determine the extent of these functional deficits after a long period post-surgical repair and rehabilitation in order to establish new methodologies that might prevent these deficits (e.g. longer rehabilitation programs). It is also important to determine which structural and functional variables are related to these deficits in order to determine the focus of the rehabilitation programs and a long-term efficacy of such programs.

The purpose of this study was to verify the existence of such plantarflexor muscle-tendon structural and functional deficits and determine which variables better explain the performance on the heel rise functional test of Achilles tendon rupture patients more than two years of surgical repair and rehabilitation. The following variables were used to achieve this goal: maximal heel rise (dependent variable), joint range of motion (ROM), torque, medial gastrocnemius muscle activation, soleus muscle activation, fascicle length (FL), pennation angle (PA), muscle thickness (MT), tendon length (TL), tendon cross-sectional area (CSA), Young's module (YM).

Methods

Study Design and Sample

This is a quasi-experimental retrospective case-control study.[17-18] Thirty male subjects signed an informed consent form prior to participating in the study, which was approved by the Ethical Research Committee of the two Universities where the study was conducted (protocol numbers 2007882 and 07/04008). Patients inclusion criteria were: male subjects, between 30 and 60 years of age, with total Achilles tendon rupture, subjected to the same surgical technique by the same surgeon at the same hospital, and with a post-operative period ranging between 24 and 34 months. Exclusion criteria included no transoperatory detection of total Achilles tendon rupture, neuromuscular diseases, diabetes mellitus, more than 3 no-shows during the accelerated treatment (only accelerated group), contraindication for the execution of maximal effort, and incapacity of performing the tests.

Subjects were divided into three different groups: control group (n = 10, no history of lower limb injury), accelerated group (n = 10) and traditional group (n = 10), with similar age. Achilles tendon rupture subjects (accelerated and traditional groups) suffered surgical repair more than 24 months prior to the study start. Patients of these groups were subjected to the same surgical technique for Achilles tendon surgical repair by the same surgeon. Subjects were allocated into the traditional or to the accelerated group according to their possibility of participating in the accelerated rehabilitation program. The traditional group remained with the affected ankle immobilized by plaster cast for six weeks and executed a home-based rehabilitation program after cast removal. The accelerated group used a removable orthosis (Robofoot type) to immobilize the ankle joint at neutral position and were subjected to a six-week (three times per week) accelerated protocol for gaining ankle joint range of motion.

Affected (AFF) and unaffected (UNA) limbs of the two patient groups were compared at the start of the study to establish possible group differences due to the different rehabilitation protocols (see statistical analysis). Right and left limbs of the control group subjects were also compared in order to determine between-limbs similarity. As similarities were observed for the AFF and the UNA limbs of the patient group and for the right and left limbs of the control group, limbs were separated into three groups (Figure 1): healthy (HEA, n = 20), unaffected (UNA, n = 20), and affected (AFF, n = 20).

Evaluation Protocol

Initially, body mass, height, leg length (distance between the lateral malleolus and the knee articular line) and limb dominance (obtained by asking which foot was used to support the limb during stair ascent and to kick a ball).[19-20-21-22] The level of physical activity was also evaluated through the short version of the International Physical Activity Questionnaire (IPAQ)[23] in order to verify if the subjects from the different groups had similar physical conditions.

Maximal height during heel rise (MHR) was measured with a metric measuring tape. Measurements were performed bilaterally during single heel rise according to clinical testing described in the literature.[24-14-25-26-27]

Total ROM was obtained with the subject seated at the isokinetic dynamometer chair (Biodex Medical System, Shirley, New York, USA) and the knee fully extended (0°). Plantar flexor ROM was measured passively by the same rater, with the centre of rotation of a plastic goniometer aligned with the ankle joint axis of rotation. Maximal ROM was determined from the neutral position (90° angle between the foot line and the shank) to the maximal plantar flexion, and the test was repeated to the maximal dorsiflexion (adapted from Frasson et al., [28]).

Maximal isometric plantar flexor torque was obtained with the subjects seated on the isokinetic dynamometer chair, hip flexed at approximately 85°, knee fully extended and the foot fixed to the foot plate with Velcro straps. Subjects were trained to execute maximal effort during a familiarization session prior to the tests. During familiarization, subjects were trained to execute MVICs at the ankle joint angles of 0º and -10º of plantar flexion. After familiarization, subjects performed two 5-sec plantar flexor MVICs at the same joint angles, which were randomly selected.

Subjects were instructed to produce maximal effort as fast as possible and to maintain maximal effort for at least 1 sec before relaxing.[29] An interval of 120 secs was observed between consecutive contractions to avoid possible fatigue effects. The test was always repeated if one of the following situations was observed: (1) when the rater or the subject realized that maximal effort was not obtained, or (2) when the contraction was not sustained for at least 1 sec. [29]

Passive surface electromyographic (EMG) electrodes (Ag/AgCl, Meditrace, Kendall, Canada) were positioned on a bipolar configuration at the skin recovering the muscle belly, in the approximate direction of the muscle fibers. Skin preparation and electrodes positioning on the muscles was performed according to the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles.[30] EMG signals were obtained from the medial gastrocnemius, soleus and tibialis anterior muscles. Muscle activation was obtained with an 8-channel EMG system (AMT-8, Bortec Biomedical Ltd., Canada) and a Windaq data acquisition system (Dataq Instruments, Akron, OH, USA; 16 bits). EMG and torque signals were synchronized on the Windaq system, and were digitized with a 2000 Hz per channel sampling frequency with an analogic-to-digital board (DI-720 16 bits, Dataq Instruments Inc. Akron, Ohio-USA).

Medial gastrocnemius muscle architecture was measured with the subject seated at the dynamometer's chair, with hip flexed and the knee fully extended according to previous studies[31-32-33] and the same ultrasound system used to measure TL. With the ultrasound probe positioned along the assumed direction of the muscle fascicles, images were captured during rest at the distal third (30%) of the muscle belly.[34] Three images were captured by the same experienced rater. Images were analized with the software ImageJ (National Institute of Health, NIH, USA), and five measurements were obtained from each image.

Achilles tendon CSA and TL were obtained according to the methodology proposed by Karaminidis and Arampatzis [35], with an ultrasound system (SSD 4000, Aloka, Tokyo, Japan) and a linear array probe (60 mm, 7.5 MHz). CSA was measured with the probe positioned perpendicular to the Achilles tendon. A small bag containing gel was used between the probe and the skin to improve the images quality to determine CSA and TL. Three images were obtained at three different points: 2 cm, 4 cm and 6 cm from the tendinous insertion at the calcaneus[36].

TL was obtained through an adaptation of the images juxtaposition method.[37] Patients were positioned prone on the dynamometer's stretcher. Markers of adhesive tape were placed transversally over the skin recovering the Achilles tendon, with the first marker placed near the calcaneus bone and the next markers proximally with a 5 cm distance between adjacent markers up to the medial gastrocnemius myotendinous junction.

Longitudinal ultrasound images were captured consecutively, with the first image at the calcaneus bone and the next images always positioned over two consecutive markers up to the medial gastrocnemius myotendinous junction. TL was obtained by the juxtaposition of the same marker obtained at two adjacent images with an image software (GIMP 2.6.11, GNU Image Manipulation Programme, www.gimp.org), allowing the Achilles tendon reconstruction. TL was considered as the distance between Achilles tendon distal insertion at the calcaneus bone and medial gastrocnemius myotendinous junction.[36]

Achilles tendon mechanical properties were evaluated during two 10-sec ramp plantar flexor maximal voluntary isometric contractions (MVICs), at neutral position (0º of plantarflexion).[38-36] Subjects were asked to gradually increase their plantar flexor torque until the MVIC was achieved. A 120-sec interval was observed between contractions to avoid possible fatigue effects, as well as changes in the tendon properties. Before the ramp MVICs three submaximal ramp voluntary contractions were performed as a familiarization procedure.

During the ramp MVICs the medial gastrocnemius myotendinous junction displacement was measured with the ultrasound system.[36] Tendon elongation was recorded with a DVD unit (R130/XAZ, Samsung Inc. Seul, South Korea) and a sampling frequency of 32 Hz.

EMG signals from the tibialis anterior muscle were recorded simultaneously with tendon elongation.[36] From the two MVICs, the one with the largest plantar flexor torque was used for data analysis. At the end of the protocol, three 5-sec dorsiflexor isometric contractions were executed at neutral position: one maximal and two submaximal. The submaximal ones were executed at an activation level smaller and higher than that measured for the tibialis anterior during the ramp plantar flexor MVICs. This procedure was used to correct the total Achilles tendon maximal force.[39-40-36]

Ultrasound images were synchronized with EMG and torque signals by means of a synchronization unit connected to the Windaq System and to the DVD recorder (HORITA Video Stop Watch VS – 50; HORITA Co., Inc., California, USA). An electrical pulse was sent simultaneously to the Data Acquisition system where EMG and torque signals were acquired and to the stopwatch connected to the video system where the ultrasound images were recorded.

Data Analysis

Absolute peak torque values were normalized by total body mass for each subject.

EMG signals were obtained from 1-sec segments at peak torque (500 ms before and after peak torque). EMG signals were filtered with a band-pass filter with cut-off frequencies of 10 Hz and 500 Hz. RMS values from each muscle were calculated for each contraction using Matlab scripts (MATLAB version 7.3.0.267, MathWorks, Inc., Natick, MA, USA).

The distance between the superficial and the deep aponeuroses of the medial gastrocnemius was measured at five different regions of each ultrasound image and the mean value was considered as the muscle thickness (MT).[41-42] The angle between the muscle fascicle and the deep aponeurosis was considered as the pennation angle (PA). Fascicle length (FL) was determined as the length of the fascicle trajectory between the superficial and deep aponeuroses.

Muscle architecture measurements were obtained with the software imageJ (National Institute of Health, USA). Three measurements of MT, PA and FL were obtained from each image by the same rater. The accuracy of these measurements was verified in a previous study with human cadaveric specimens.[43] Measurement reproducibility was verified with the Intra-Class Correlation Coefficient (ICC).

Maximal force at the Achilles tendon was obtained through the sum of the maximal plantar flexor torque to the torque generated by the dorsiflexor muscles during plantar flexion.[39-40] Dorsiflexor torque was estimated from the linear relation established between the tibialis anterior activation obtained at three different activation levels: (a) at rest, (b) producing a dorsiflexor torque that generated an EMG signal with smaller amplitude than that produced during maximal plantar flexion, and (c) a dorsiflexor torque that generated an EMG signal of the tibialis anterior that was higher than that generated during maximal plantar flexion. EMG signal amplitude was determined by visual inspection of the voltage produced by the muscles on a digital oscilloscope (MO – 2250DC, 250MHz, Minipa, São Paulo, Brasil).

Tendon elongation and tendon strain were determined from images previously stored on the DVD. Images were transformed in AVI format using the BitRipper software (Binotex, USA). The AVI file was tracked frame-by-frame with the Virtual Dub software (Avery Lee, USA) in order to select the desired images.

The stress-strain relation was determined through mathematical scripts in MATLAB (MATLAB version 7.3.0.267, MathWorks, Inc., Natick, MA) and was obtained by the relation between the maximal torque from the ramp MVIC and the corresponding tendon elongation. Values of force, tendon elongation, stress (force/tendon cross-sectional area) and strain (tendon length after elongation/initial tendon length) were obtained at 0, 20, 40, 60, 80 and 100% of the ramp MVIC.[36] A second order linear regression was used to construct the stress-strain curve. Young's Module was determined as the inclination of the stress-strain relation between the levels of 60% and 80% of maximal torque.[8]

Statistical Analysis

Sample size was calculated with the software G*POWER 3.1.3 (Frauz Faur Universität Kiel, Alemanha), with an effect size of 0.30, and α=0.05 and a power of 0.80, using the multiple linear regression test (predictor variables = 10 and predicted variable = 1) as the statistical test to define sample size.

Data are presented by mean and standard deviation for the anthropometric variables (body mass, height, and leg length), dependent variable (calcaneus elevation height) and independent variables (MT, FL, PA, ROM, maximal isometric torque, EMG activity of medial gastrocnemius and soleus, Achilles tendon CSA, TL and Young's Module). Data normality was determined by the Shapiro-Wilk test, whereas data homogeneity by the Levene test.

An independent Student's t-test was used (1) to evaluate possible between-groups differences at the level of physical activity, (2) to compare the heel height between the AFF and UNA limbs of the control group during the hell elevation functional test. A paired samples Student's t-test was used to compare the heel height between the right and left limbs of the control group during the hell elevation functional test.

A one-way ANOVA with a Bonferroni post-hoc test was used to compare all independent variables between the three-different limb-groups: HEA, UNA and AFF. In addition, the Effect Size was calculated for the between-groups comparison. Effect Sizes were determined according to the Cohen's Model[44] as trivial (<0.25), small (0.25-0.49), moderate (0.5-1.0) and large (>1.0).

A Stepwise Multiple Linear Regression Model was used to identify which independent variables (joint ROM, torque, medial gastrocnemius muscle activation, soleus muscle activation, FL, PA, MT, TL, tendon CSA, YM) were able to determine the performance at the heel elevation functional test (dependent variable). [45]

The software SPSS 20.0 was used for all statistical tests with a significance level for α = 0.05.

Results

No between-groups differences were observed for the anthropometric variables as well as for the Level of Physical Activity (Table 1).

The height of the heel elevation functional test was similar (p=0.891, ES=0.10) between the right (14.3 ± 0.9 cm) and left (14.4 ± 1.1 cm) limbs of the control group. Similar results were observed for the UNA limbs (p=0.404, ES=0.40) of the traditional (12.5 ± 1.3 cm) and accelerated (11.6 ± 2.9 cm) groups and for the AFF limbs of these two patient groups (traditional = 10.8 ± 1.7 cm, accelerated = 9.7 ± 2.3 cm; p=0.231, ES=0.54). Therefore, results from both limbs of the control group were grouped into a healthy limb group (HEA, n=20), whereas limbs from the patient group were grouped into the unaffected (UNA, n=20) and affected (AFF, n=20) limb groups.

HEA heel height was higher compared to the UNA (~18%; p=0.001; ES=1.26) and AFF (~40%; p<0.001; ES=2.54) limb-groups, and was also higher at the UNA compared to the AFF limb (~19%; p=0.008; ES=0.86) (Table 2).

Ankle plantiflexor ROM was similar between the three limb-groups (HEA x UNA p=1.000; HEA x AFF p=0.567; UNA x AFF p=0.701).

Maximal isometric normalized plantar flexor torque was similar between HEA and UNA limbs (p=0.767). However, maximal isometric torques were higher at the HEA (~29%; p<0.001; ES=1.40) and at the UNA (~22%; p=0.003; ES=1.43) limbs compared to the AFF limb.

The relative gastrocnemius medialis muscle activation was similar between the three limb-groups (p>0.05). Soleus muscle activation was also similar between the HEA and UNA and HEA and AFF limbs (p>0.05). However, soleus muscle activation was lower at the AFF compared to the UNA limb (~22%; p=0.004; ES=1.26).

Medial gastrocnemius FL was similar for the HEA and UNA limbs (p=0.052) and both were higher compared to the AFF limbs (~23%, p<0.001, ES=2.60; 14%, p<0.001, ES=1.42, respectively). PA was higher at the AFF compared to the HEA limbs (~11%, p=0.007, ES=1.32), but was similar between the AFF and UNA limbs (p>0.05). MT was similar for the HEA and UNA limbs (p=0.45), but was higher compared to the UNA limbs (15%, p<0.001, ES=1.20; 10%, p=0.031, ES=0.92, respectively).

Achilles TL of the AFF limb was higher compared to the HEA limb (~4%, p=0.019, ES=0.82), but similar between the UNA and AFF limbs (p=0.067) and between the HEA and UNA limbs (p=1.000). Achilles CSA was higher at the AFF compared to the HEA (~124%, p<0.001, ES=3.90) and UNA (~115%, p<0.001, ES=3.75) limbs. However, CSA was similar between the HEA and UNA limbs (p=1.00).

Young’s module was higher at the HEA and UNA limbs compared to the AFF limb (~113%, p<0.001, ES=2.99; ~138%, p<0.001, ES=2.45, respectively), but was similar between the HEA and UNA limbs (p>0.05).

Multiple linear regression indicated that Achilles tendon CSA and plantiflexor torque had a significant relation with the heel elevation functional test performance for the HEA limb (p=0.005; equation 1). For the UNA limb, only the EMG signal of the medial gastrocnemius muscle showed a significant relation with the heel elevation functional test performance (p=0.013; equation 2).

For the AFF limb none of the independent variables was accepted by the multiple linear regression model to explain the heel elevation functional test performance.

1. $Heel\ Elevation = (-0.706 * CSA - \ 0.090) + (-0.554 * Torque - 1.604)$
2. $Heel\ Elevation = -0.554 * MG\ EMG - 6.318$

Where:

CSA = Achilles tendon anatomical cross-sectional area;

Torque = plantiflexor torque at the neutral position normalized by body mass;

MG EMG = medial gastrocnemius muscle myoelectrical activity (RMS values).

Discussion

The main results of the present study showed that there is a functional deficit in both limbs of the patient group compared to the healthy control group. More specifically, the AFF limb-group had the smaller performance at the heel elevation functional test, followed by the UNA and by the HEA limbs. The fact that the UNA limb also presented an 18% deficit in this functional test is evidence that the AFF limb limitations do affect negatively the UNA “healthy” contralateral limb.

The fact that the effect size was large for almost all significant comparisons between the AFF and the healthy limbs, being moderate only for the tendon length between HEA and AFF and for heel height between UNA and AFF limbs, is evidence that the observed differences were indeed present and are clinically relevant.

The second main outcome of this study is that Achilles tendon CSA and maximal isometric plantiflexor torque are able to explain this higher performance at the heel elevation test of the

HEA limb. This makes sense, as there should exist a direct relation between the tendon CSA and the amount of torque produced and transferred to the bone by the tendon. However, for the UNA limb, only medial gastrocnemius activation was able to explain the heel elevation. This means that the changes that occurred at the AFF limb with injury did have a significant impact at the UNA limb, as tendon CSA and maximal torque cannot explain heel height anymore. Apparently, this loss in tendon structure and in plantarflexor torque production of the AFF limb is probably responsible for some structural and functional loss at the UNA limb, leading to an increase in the medial gastrocnemius activity probably in an attempt of the central nervous system to compensate for the loss in plantarflexor torque-production capacity. In addition, the multiple losses (structural and functional) of the AFF limb lead to the fact that none of the independent variables is able to explain the functional performance at the heel elevation test in this group.

Achilles tendon CSA was augmented after the surgical repair. The increased CSA is a result of the scar tissue that is produced by fibroblasts at the rupture site. This conjunctive tissue is associated initially with the inflammatory process followed by tissue regeneration.[46-8] The amount of this scar tissue is dependent on the duration of the immobilization period and on the amount of load decrease at the tendon post-surgery, which might influence the tendon remodelling.[47] Early mobilization appears to be important for this remodelling, as load applied to the scar tissue appears to improve the type and the direction of collagen deposition at the suture site.[48] However, Achilles tendon thickness or CSA increase has been observed after 12 months[46-49] or even after 24-33 months[8] after surgical repair, with a CSA increase of about 113% at the AFF compared to the UNA limb.

Plantarflexor torque deficits at the AFF compared to the UNA limb have been reported in the literature 21 months post-reconstructive surgery.[4] According to Maffulli et al.[50], there is an association between this reduction on the force production capacity at the AFF limb and the patient's life style adopted after Achilles tendon rupture. It is interesting to observe that about 46% of the patients that suffered total Achilles tendon rupture do not return to the same level of physical activity of that pre-rupture.[51] This might explain why there is no complete recovery of the tendon tissue, and why none of the independent variables was able to explain the performance of the heel elevation test at the AFF limb.

These life style changes might also explain the results observed at the contralateral "healthy" side. The fact that medial gastrocnemius activation was the only independent variable able to explain the performance of the heel elevation test at the UNA limb appears to indicate a possible compensatory neural mechanism aimed at protecting the injured weak side by increasing the control of the contralateral side.[52-53-7]

The observed functional deficits at the AFF limb compared to the contralateral UNA limb have been observed in previous studies for periods ranging between 1 and 10 years post-surgical repair.[54-14-15-25] Although it is not completely clear which variables are responsible for these deficits, our results indicate that torque and tendon CSA are important variables that explain a good performance on the heel elevation test at the HEA limb group. This functional deficit in heel elevation has been observed even 10 years post-surgical repair and has been related to the force production decrease at the AFF limb.[15]

One of the most important consequences of these deficits are the changes in motor strategies, as we observed at the UNA limb. These motor changes appear to be a strategy to compensate the change in ROM during functional daily activities, and, in the end, they might constitute a risk factor for new pathological conditions[55], probably due to the changes in mechanical load at both sides of the patients. One example of these motor changes is the pathological gait observed by Don et al.[10] 24 months post-surgical repair, who related these functional changes to an eccentric force deficit of the shank muscles. Silbernagel et al.[25] also found complications such as a reduction at the heel height elevation, muscle weakness and gait abnormalities that persisted 12 months post-surgery. These authors related the deficit at the functional test with a larger Achilles tendon length post-surgery.

The above results are important in several aspects for the rehabilitation area. First, they show that the AFF limb has a significant impact at the contralateral UNA limb, and therefore treating the affected limb is important to get both limbs at a healthy condition. Second, they show that a rehabilitation protocol needs to be long in duration, as structural and functional changes at the tendon need a longer time compared to the changes observed in the muscle. Third, the show an increased risk for re-rupture at the AFF side and/or rupture at the contralateral UNA side. Fourth, they also show that combating these deficits might need not just an early or accelerated load of the injured tendon, but that full recovery might take several months or even years to produce a significant adaptation of the muscle-tendon unit to its full recovery.[10-54] Fifth, the following aspects should be emphasized in such a rehabilitation program: increase in soleus activation, increase in tendon CSA, and increase in maximal plantarflexor torque, increase in Young’s module, increase in fascicle length and increase in muscle thickness for a full recovery.

Although there is a larger body of knowledge regarding the problems affecting the Achilles tendon, the best treatment/rehabilitation protocol is still controversial.[15-56] Nevertheless, in our opinion, eccentric training of the AFF limb is probably one of the main components of a rehabilitation program. Eccentric training will produce the necessary overload to determine a series of structural and functional adaptations that are needed for the full recovery as mentioned above. Among these adaptations are: an increase in tendon stress capacity, realignment of collagen fibres at the scar site, possible exchange for stronger collagen fibres (from type 3 to type 1) and possible reduction of the scar tissue and tendon CSA. All the above will help to increase the Achilles tendon Young’s module. It will also help in both serial and parallel sarcomeres increase, leading to increased muscle strength and to a correction of optimal length for force production. Finally, it will also help to increase soleus muscle activation that was probably decreased at the AFF side for being a monoarticular muscle[7], and therefore more prone to suffer with the injury, as it is used for all daily-life activities. Altogether, these changes will correct gait changes and will allow for a correct hell height during the heel elevation functional test, reducing the risk factors for re-injury or for a new injury. Such a long-term rehabilitation program will also help counteracting the kinesiophobia that is characteristic during dorsiflexion in these patients[57], as they will gain confidence in the recovery through the abovementioned objective and measurable changes. However, care should be taken when applying such programs due to the elevated load of eccentric exercise at the passive tissues, which might constitute a risk factor for re-injury if the tendon tissue is not sufficiently strong.

Clinical Messages

- More than two years after total Achilles tendon rupture and rehabilitation, patients still present functional deficits.
- The deficits are larger at the affected limb followed by the contralateral limb.
- Physical Therapy should be mainly focused in rehabilitating the tendon anatomical cross-sectional area and torque production (both actively and passively).

Contributors

ARL: Conception and design, data analysis, drafting, revising and final approval of the manuscript.
JMG: Conception and design, data acquisition, data analysis, revising and final approval of the

manuscript. FJL: data analysis, revising and final approval of the manuscript. AM, RDO, VBF: Data acquisition, data analysis, revising and final approval of the manuscript. MAV: Conception, design, training and supervision, data analysis and interpretation, English review and final approval of the manuscript.

Competing Interests

The authors declare no competing interests.

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Conflict of Interest Statement

The Authors declare that there is no conflict of interest.

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Table 1. Anthropometric and clinical characteristics of the three groups.

	CG	TRA	ACC	p-value
Age (years)	44.70 ±9.71	44.20 ±9.31	44.10 ±8.70	0.682
Body mass (Kg)	81.58 ±12.88	82.31 ±9.05	84.79 ±7.45	0.060
Heigth (m)	1.76 ±0.04	1.72 ±0.04	1.74 ±0.06	0.959
IPAQ	2.5 ±1.1	3.0 ±1.1	2.6 ±1.2	0.570

CG= Control Group; TRA = Traditional Group; ACC = Accelerated Group.

Table 2. Between-groups comparison of structural, mechanical and functional results.

	HEA	**UNA**	**AFF**	**Significant differences (Effect Size)**		
				HEA X UNA	**HEA X AFF**	**UNA X AFF**
Plantiflexor ROM (°)	48.4 ± 5.9	48.0 ± 9.2	44.7 ± 10.7	1.000 (0.05)	0.567 (0.43)	0.701 (0.33)
Norm Torque (Nm/kg)	1.9 ± 0.3	1.9 ± 0.29	1.5 ± 0.3	0.767 (0.00)	**<0.001* (1.40)**	**0.003* (1.43)**
RMS-SOL (%)	1.0 ± 0.2	1.1 ± 0.1	0.9 ± 0.2	0.655 (0.00)	0.103 (0.50)	**0.004* (1.26)**
RMS-MG (%)	1.0 ± 0.3	1.1 ± 0.2	0.9 ± 0.2	0.919 (0.39)	0.557 (0.39)	0.063 (1.00)
Tendon Length (mm)	235 ± 11.0	237 ± 8.8	245 ± 13.4	1.000 (0.17)	**0.019* (0.82)**	0.067 (0.74)
Tendon CSA (cm^2)	60.2 ± 7.4	62.8 ± 7.8	135.0 ± 26.1	1.000 (0.34)	**<0.001* (3.90)**	**<0.001* (3.75)**
Young's Module (Mpa)	824 ± 188	922 ± 297	386 ± 86	0.433 (0.39)	**<0.001* (2.99)**	**<0.001* (2.45)**
FL (% Tibia Length)	11.1 ± 0.7	10.4 ± 1.0	9.0 ± 0.9	0.052 (0.87)	**<0.001* (2.60)**	**<0.001* (1.42)**
PA (°)	17.6 ± 1.3	19.1 ± 2.4	19.6 ± 1.7	0.061 (0.78)	**0.007* (1.32)**	1.000 (0.24)
MT (mm)	13.6 ± 1.6	13.0 ± 1.2	11.9 ± 1.2	0.447 (0.42)	**<0.001* (1.20)**	**0.031* (0.92)**
Heel Height (cm)	14.3 ± 0.9	12.1 ± 2.3	10.2 ± 2.1	**0.001* (1.26)**	**<0.001* (2.54)**	**0.008* (0.86)**

ROM = Range of Motion; RMS-SOL = Root Mean Square Soleus; RMS-MG = Root Mean Square Medial Gastrocnemius; CSA = Cross-Sectional Area; FL = Fascicle Length; PA = Pennation Angle; MT = Muscle Thickness; HEA = Healthy; UNA = Unaffected; AFF = Affected.

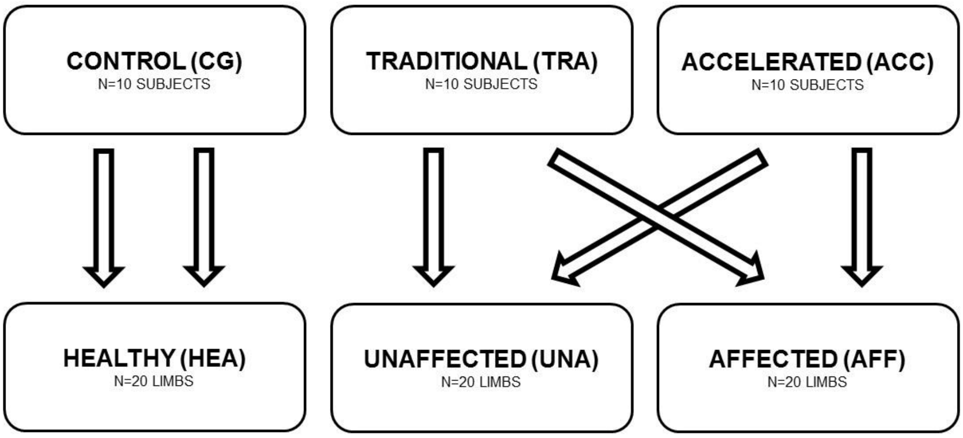

Figure 1. Limbs were grouped according to their neuromuscular similarities.

ANEXO I – NORMAS PARA PUBLICAÇÃO DA REVISTA CLINICAL REHABILITATION

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- Acknowledgements, author contributions, competing interests and funding support
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