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DEFICITS OF CALF MUSCLES STRENGTH AND RATE OF FORCE DEVELOPMENT AFTER ACHILLES TENDON RUPTURE

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Abstract

Many studies, investigating biomechanical properties of plantar flexors muscle-tendon unit after ATR surgery, reported an incomplete calf muscle contractile functional recovery. However, these studies only investigated the plantar flexors muscle function failing to provide information about the adaptive changes in motor strategy. In fact, the development of adaptive changes in motor strategies, due to both mechanical and neural factors, may result in pathological musculoskeletal conditions over the long term. Understanding physiological calf muscle changes due to long-term immobilization may help prevent Achilles tendon re-rupture cases.

Keywords: *MVC torque, neuromechanical outcomes, physiotherapy.*

Introduction

The Achilles tendon is the thickest and the strongest tendon in the human body (Maffulli, Oliva, & Ronga, 2013; Wang, Chiang, Chen, Shih, Huang, & Jiang, 2013; Bressel & Mc Nair, 2001). It is established that acceleration/deceleration mechanism explains 90% of all cases of Achilles tendon rupture (ATR) (Arnold, Hamner, Seth, Millard, & Delp, 2013; Maffulli et al., 2013; Finni, Hodgson, Lai, & Edgreto, 2006). One of the causes of ATR may be the inadequate relationship between the small cross-sectional area of the tendon and external forces (Kongsgaard, Aagaard, Kjaer, & Magnusson, 2005). After ATR, muscle strength and functional ability decrease (Horstamann, Lukas, Merk, Brauner, & Mündermann, 2012) and neural and mechanical transduction in the muscle – tendon unit are decreased (Doral, Alam, Bozkurt, Thurnan, Atay, Donmez, & Maffulli, 2010; Smigielski, 2008). It is well established that prolonged Achilles tendon immobilization leads to calf muscle atrophy (Wang et al., 2013; Earp, Kraemer, Cormie, Volek, Aresh, Joseph, & Newton, 2011), which in turn leads to decreased isokinetic and isometric muscle strength for 60 weeks after surgery. Horstamann (2012) and colleagues have shown that plantar flexion muscle strength remains reduced for 10 years after ATR surgery. This is associated not only with muscle atrophy, but also with the smaller cross-sectional area of the repaired tendon. Within one year after ATR surgery plantar flexion (PF) muscle activation and tibialis anterior muscle co-activation remain altered (Wang et al., 2013). This may be explained by altered neural control and tissue mechanical properties in the ankle joint region (Wang et al., 2013), which suggest slow force production (Suetta, Aagaard, Roset, Jakobsen, Duus, Kjaer, & Magnusson, 2004).

The rate of force development (RFD) can be defined as the rate of rise in contractile force at the onset of muscle contraction (Hernández-Davó & Sabido, 2014; Oliveira, Oliveira, Rizatto, & Denadai, 2013; Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002) and can be considered as characteristic of explosive strength (Maffiuletti, Aaagaard, Blazevich, Folland, Tillin, & Duchateau, 2016; Aagaard et al., 2002). It has been demonstrated that RFD is influenced by different physiological parameters at early (<100ms) and late phase (>100ms) of the isometric contractions (Oliveira et al., 2013). The early phase is influenced by intrinsic muscle contractile properties (Andersen, Andersen, Zebis, & Aagaard, 2010) and neural drive (Oliveira et al., 2013; Gruber & Golhofer, 2004), whereas the late phase is influenced by muscle cross-sectional area (Suetta et al., 2004), neural drive (Aagaard et al., 2002) and stiffness of tendon-aponeurosis complex (Bojsen-Møller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005). Moreover, the RFD compared to maximal voluntary contraction (MVC) seems to be more related with the functional daily tasks (Maffiuletti et al., 2016; Oliveira et al., 2013), also to be more sensitive to detect acute and chronic changes in neuromuscular function (Maffiuletti et al., 2016; Gruber & Gollhofer, 2004). The ability to generate high muscular strength within a short period is of functional importance for active joint stabilization (Blazevich, Cannavan, Horne, Coleman, & Aagaard, 2009; Holtermann, Roeleveld, Vereijken, & Ettema, 2007; Gruber & Gollhofer, 2004). Also, the ability to develop a rapid rise in RFD becomes important for subjects with unilateral ATR surgery because disturbed neuromechanical properties of the muscle–tendon complex after ATR surgery affect plantar flexors' RFD (Hernández-Davó & Sabido, 2014; Doral et al., 2010; Smigielski, 2008; Suetta et al., 2004). However, there is a lack of information about the calf muscle RFD changes during one-year period for persons after unilateral ATR surgery. We hypothesized that, within the first year after unilateral ATR surgery, we would observe the greater calf muscle RFD in non-injured than in injured leg, but the total calf RFD torque deficit between legs would decrease in plantar flexion and dorsiflexion tasks.

The aim of our study was to (1) estimate the isometric calf muscles maximal voluntary contraction (MVC) torque and rate of force development (RFD) of plantar flexion (PF) and dorsiflexion (DF) muscles at a 1-year follow-up in subjects with unilateral ATR surgery of non-injured and injured legs and (2) compare the calf muscles MVC torque and RFD between non-injured and injured legs over the first year after unilateral ATR surgery.

Methods and organization

Subjects

Eight male subjects with ATR (age, 36±4 years) volunteered to participate in the study. All participants with Achilles tendon rupture had had Achilles tendon surgery 7-9 weeks previously and underwent 10 rehabilitation procedures. Moreover, their ankle range of motion was not less than 15^{o} ankle angle of dorsal and plantar flexion and they could walk without pain. All experimental procedures were performed in accordance with the Declaration of Helsinki, and all participants read and signed an informed consent form that was approved by the Lithuanian Bioethics Committee.

Protocol

The details of the experiment were explained to the participants before testing. All measurements for both groups were taken 7 times: first for the ATR group, 7-9 weeks after unilateral ATR surgery and no less than after 10 rehabilitation procedures, second – after 8 weeks of physical therapy (PT) for ATR surgery group. The remaining five measurements were performed every two months in one-year period (see Figure 1). After 8 weeks of PT, participants were encouraged to keep exercising at home. A quantitative survey of the MVC and RFD of plantar muscles was performed using "The Biodex medical System PRO 3".

The sensitivity of the Biodex system for torque measurement is ±1.36 Nm. The participants were secured on an adjustable chair in a slightly reclined position: the hip was flexed at 75º, the knee was flexed at 30º and the participants were strapped at the chest. The foot was held in place by a heel block and was tightly attached to the plate by two straps. One strap was placed around the foot, 1-2 cm proximal to the metatarso-phalangeal joint of the toe, and the second strap was placed around the foot, just below the ankle joint. The position of the subject was adjusted to obtain a 90º angle for the ankle (neutral position 0º). To correct the effect of gravity on the measured joint movements, the passive mass of the foot was measured in the dynamometer at 15º ankle angles. All subjects were tested without shoes.

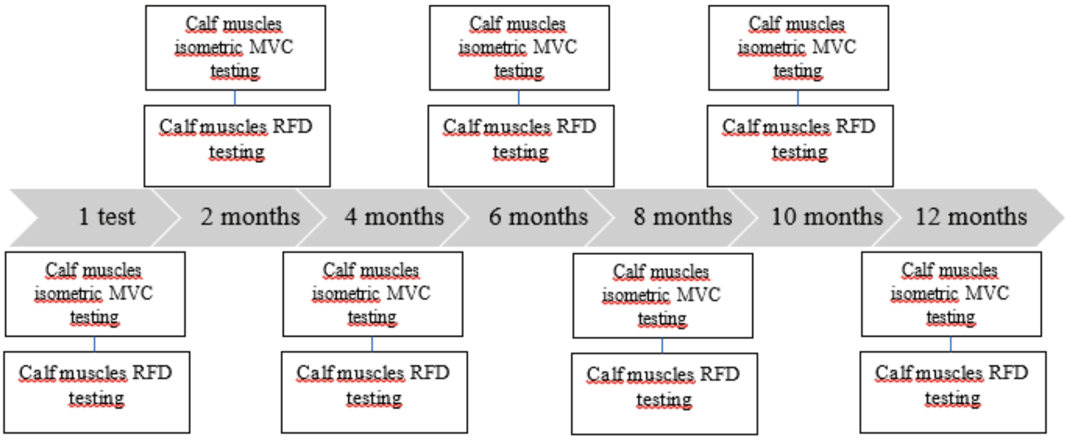

Fig. 1. Scheme of protocol

The MVC torque of PF muscles was measured in the non-injured leg (UIL) and injured leg (IL). The test started from the UIL. The MVC torque of PF muscles in each participant was tested at randomized -15º, 0º, and 15º ankle angles (Solianik et al., 2010). For each ankle angle, the participants performed two ankle flexion and extension repetitions. The rest period was 30 s between repetitions, and 60 s between different ankle angles.

The RFD of PF and DF muscles was measured in the UIL, IL legs. The RFD of PF and DF muscles was tested at -15º, 0º, 15º ankle angles, which corresponded to the ankle angles used for MVC torque measurement. RFD was calculated from the individual MVC development records and was defined as the slope of the force time curve (Δforce/ Δtime) over time intervals of 0-30, 30-50, 50-100, 100-200 ms relative to the onset of the force (Gruber & Gollhofer, 2004). Force values were determined at 30, 50, 100 and 200 ms relative to the onset of the force.

PT was administered for 8 weeks, three times per week, with one session lasting 30 min. The PT programme was directed towards the recovery of motion, power, strength and proprioception. All exercises were performed without pain, and the intensity increased over the 8-week PT programme period. Each session started with a gentle 10 min warm-up. In cases of pronounced ankle joint stiffness, ankle and subtalar joint mobilization was also performed to increase range of motion. For triceps surae muscles, stretching exercises were started gently and became more intensive. Eccentric exercises was applied to increase PF muscle strength. Resistance exercise was started at isometric open chain exercise and gradually increased to isokinetic closed chain exercise. Exercise for body balance and weight bearing were applied to both legs for proprioception improvement.

Statistical analysis

The research data were processed employing Microsoft Excel 2010 software for mathematical statistical analysis and all statistical analysis was performed using SPSS 22.0 software. The non-parametric Wilcoxon test was performed to analyse the calf muscle isometric (at -15°, 0°, 15° ankle angles) MVC torque, and RFD (at 30 ms, 50 ms, 100 ms, 200 ms time/force curves) differences between UIL vs. IL legs. A mixed analysis of variance (ANOVA) and Tukey HSD test were used to analyse the changes in time of calf muscle MVC torque of isometric MVC and RFD in UIL and IL legs. The data are reported as the group mean value ± standard deviation (SD). The level of significance was set at $p<0.05$.

Results

The plantar flexion and dorsiflexion muscle MVC torque data are presented in Table 1. At a **-15**° ankle angle, **plantar flexion** muscle MVC torque was greater ($p<0.05$) in UIL than IL at 1, 2 and after 6 months. At a **0**° ankle angle, the plantar flexion muscle MVC torque was greater ($p<0.05$) in UIL than IL at 2, 4, 6, 10 and after 12 months. At a **15**° ankle angle, the plantar flexion muscle MVC torque was greater ($p<0.05$) in UIL than IL at 6, 10 and after 12 months.

At a **-15°** ankle angle (Table 1), **dorsiflexion muscle** MVC torque was greater ($p<0.05$) in UIL than IL at 2, 6, 8, 10 and after 12. At a **0°** ankle angle, dorsiflexion muscle MVC torque was greater ($p<0.05$) in UIL than IL at 1, 2, 6 and after 8 months. At a **15°** ankle angle, dorsiflexion muscle MVC torque was greater ($p<0.05$) in UIL than IL at 1, 2, 6 and after 8 months.

Table 1. Calf muscles MVC torque at -15; 0; 15° ankle angles

Month	Ankle angle (°)	Plantar flexion		Dorsifexion	
		UIL (Nm)	IL (Nm)	UIL (Nm)	IL (Nm)
1	-15	127.6±20.5*	87.6±19.9	23.6±7.3	13.5±2.3
	0	92.2±5.8	71.3±9.3	43.8±6.01*	25.1±3.3
	15	69.2±6.8	46.3±6.1	41.6±1.9*	29.5±4.1
2	-15	122.7±14.1*	90.4±7.8	24.9±6.8*	14.1±2.2
	0	110.8±11.6*	84.4±10.7	41.9±4.2*	34.±1.4
	15	70.3±5.1	56.3±12.8	45.6±2.5*	35.5±2.2
4	-15	122.3±17.6	90.6±6.1	29.6±14.1	18.9±22.5
	0	115.6±14.4*	86.9±7.9	36.3±15.1	37.3±5.4
	15	69.9±24.2	61.4±15.7	49.5±14.9	45.18±7.1
6	-15	134.5±9.9*	110.9±5.8#	28.9±3.4*	18.9±3.2#
	0	113.6±10.4*	89.7±18.4	42.3±3.9*	34.8±3.6
	15	75.1±8.6*	58.7±9.1	49.6±6.9*	44.1±3.9

Continued Table 1

8	-15	135.2±16.4	116.7±6.7	25.5±0.7*	20.1±1.3
	0	118.1±8.1	97.3±8.5	38.6±2.1**	33.9±1.5
	15	79.4±9.6	62.1±7.1	42.9±4.01*	38.7±3.4
10	-15	140.2±5.3	119.8±4.9#	26.9±2.4*	21.9±1.2#
	0	119.8±7.1*	96.8±8.1	37.1±0.7	34.4±2.1
	15	80.8±5.6*	64.3±9.1	40.9±3.2	37.1±2.4
12	-15	149.2±6.1	121.6±12.2#	28.5±4.01*	20.9±3.4#
	0	123.5±6.6*#	98.9±9.9	38.4±1.5	34.6±3.9
	15	83.2±4.7*	61.3±10.4	42.9±3.4	39.9±2.6

Observations: Data are shown as mean±standard deviation; UIL – non-injured leg; IL – injured leg; *– p<0.05, differences between the UIL and IL leg; **– p≥0.001 comparing values between UIL vs IL leg at -15°, 0°, 15° ankle angles; # – p<0.05 comparing muscle MVC torque values over time in UIL and IL legs.

The plantar flexion and dorsiflexion muscle MVC torque or RFD data at a -15° ankle angle are presented in Table 2. At a **-15**° ankle angle **plantar flexion** muscle MVC torque of RFD was greater (p<0.05) in UIL than IL in the first month in 100 ms and 200 ms; after 4 months in 200 ms; after 6 months in 50 ms, 100 ms, 200 ms; after 8 months in 30 ms, 50 ms, 100 ms and 200 ms; after 10 months in 30 ms and 50 ms; and after 12 months in 200 ms time.

At a **-15**° ankle angle (Table 2.), **dorsiflexion muscle** MVC torque was greater (p<0.05) in UIL than IL in the first month in 30 ms and 200 ms time; after 4 months in 50 ms time; after 8 months in 30 ms, 50 ms and 50 ms time.

Table 2. Calf muscles MVC torque of RFD at -15° ankle angle

Month	RFD (ms)	Plantar flexion		Dorsiflexion	
		UIL (Nm)	IL (Nm)	UIL (Nm)	IL (Nm)
1	30	13.1±5.1	14.5±4.4	9.3±3.94*	7.6±4.5
	50	16.4±6.7	15.9±4.2	10±3.69	8.9±3.4
	100	29.7±8.8*	20.9±4.2	109±3.1	11.1±5.7
	200	47.6±16.5*	23.9±5.4	15.6±4.7*	12.3±2.9
2	30	16.6±3.4	14.4±8.9	10.3±2.6	8.4±4.6
	50	19±3.1	17.5±9.6	11.1±2.9	8.7±3.3
	100	27.8±13.2	27.3±6.7	12.4±2	11.5±4.3
	200	45.2±14.2	33.1±9.1	17.9±4.1	14.5±6.1
4	30	17.2±7.6	12.9±4.7	11.7±4.5	10.4±5.6
	50	19.8±6.4	16.2±4.8	13.7±4.9*	10.7±5.5
	100	26.6±7.9	21.3±4.3	17.2±7.5	12.2±4.5
	200	42.8±11.5*	29.3±10.7	22.1±10.1	14.2±2.7
6	30	16.6±1.8	13.3±5.6	11.4±6.5	10.9±4.9
	50	19.2±2.9*	17.1±4.7	12.7±6.2	11.5±4.5
	100	26.1±1.8*	21.5±5.6	14.3±5.2	11.9±4
	200	41.1±7.1*	29.9±4.9	23±4.9	15.8±3.4
8	30	19.8±6.4*	16.2±4.8	12.8±0.5*	11.5±1.9
	50	19.2±2.9*	13.1±4.7	12.8±0.6*	12.9±1.6
	100	26.1±1.8*	17.5±5.6	17.9±1.66	15.2±1.4
	200	42.8±11.5*	29.3±10.7	21.4±1.4	18.8±1.8

Continued Table 2

10	30	16.6±1.8*	13.3±5.6	13.1±3.3	9.7±0.7
	50	19.2±2.9*	13.1±4.7	15.4±4.1	10.8±0.9
	100	26.1±1.8	17.5±5.6	14.9±2.9	14.4±0.8
	200	41.1±7.1	29.9±4.9	20.8±0.2	19.4±3.7
12	30	18.4±2.1	12.6±5.03	13.9±0.9	10.4±0.8
	50	19.5±2.6	13.9±4.8	15.2±1.4	11.8±0.8
	100	23.9±0.8	16.9±2.9	16.4±1.9	13.3±1.2
	200	49.3±4.7	26.2±1.2	21.9±2.3#	18.8±1.9

Observations: Data are shown as mean±standard deviation; UIL – non-injured leg; IL – injured leg; *– p<0.05, differences between the UIL and IL leg; **– p≥0.001 comparing values between UIL vs IL leg at -15°, 0°, 15° ankle angles; # – p<0.05 comparing muscle MVC torque values over time in UIL and IL legs.

The plantar flexion and dorsiflexion muscle MVC torque or RFD data at a 0° ankle angle are presented in Table 3. At a **0**° ankle angle, **plantar flexion** muscle MVC torque was greater (p<0.05) in UIL than IL in first month in 200 ms time.

At a **0**° ankle angle (Table 3), **dorsiflexion** muscle MVC torque was greater (p<0.05) in UIL than IL in the first month in 50 ms, 100 ms and 200 ms time; after 2 months in 30 ms (d=0.49) time; after 12 months in 30 ms and 100 ms time.

Table 3. The calf muscles MVC torque of RFD at 0° ankle angle

Month	**RFD (ms)**	**Plantar flexion**		**Dorsiflexion**	
		UIL (Nm)	**IL (Nm)**	**UIL (Nm)**	**IL (Nm)**
1	30	9.5±1.8	7.5±1.8	10.9±3.5	8.6±1.9
	50	11.6±2.2	10.2±5.2	11.7±3.7*	10.1±4.9
	100	20.4±3.2	14.9±7.1	18.3±4.3*	13.7±6.3
	200	38.6±3.5*	25.9±9.1	25.2±4.5*	18.7±6.4
2	30	10.8±5.1	8.6±4.4	14.3±2.7*	10.8±3.4
	50	13.7±5.4	10.7±3.6	15.3±3.4	12.2±5.3
	100	22.6±8.7	21.7±9.3	21.7±5.3	18.9±6.8
	200	39.9±14.4	39.2±9.9	29.5±8.5	25.1±8.4
4	30	9.9±5.2	8.8±0.9	15.3±4.8	11.1±1.9
	50	11.9±5.3	11.8±0.9	18.4±5.7	14.7±1.8
	100	21.1±4.7	18.8±6.6	24.9±8.7	20.6±2.2
	200	37.4±8.8	32.3±11	31±11.2	26.9±4.1
6	30	13.6±6.8	11.8±5.1	14.5±3.6	10.7±1.9
	50	17.1±8.2	15.4±5.7	17.9±3.2	13.7±1.7
	100	24.9±9.8	25.7±5.7	20.4±3.1	17.7±1.3
	200	41.5±2.9	37.9±9.5	28.4±5.2	26.1±1.4
8	30	10.1±2.2	9.2±1.9	13.6±2.3	9.2±3.7
	50	11.4±2.3	11.9±2.2	15.1±2.9	12.5±4.1
	100	18.9±3.6	17.1±1.4	18.5±2.3	16.9±3.9
	200	31.2±7.5	24.6±3.7	25.6±4.6	21.6±4.4

Continued Table 3

10	30	13.7±1.9	11.4±2.3	14.5±2.4#	10.7±1.4
	50	14.9±1.8	12.4±1	13.7±2.9#	11.5±1.2
	100	18.3±1.1	17.7±0.7	19.3±1.4	13.7±1.8
	200	25.2±5	24.8±3.3	27.3±1.2	27.9±2.8#
12	30	13±0.9	10±1.2	18.2±2.3*#	10.8±3.9
	50	13.6±1	12.5±0.9	18.6±1.8#	13.6±2.1
	100	18.7±1	17.9±1.9	24.6±1.4*#	15.6±2.9
	200	31.3±6.3	30.8±8.3	30.3±1.5	28.9±3.6#

Observations: Data are shown as mean±standard deviation; UIL – non-injured leg; IL – injured leg; *– $p<0.05$, differences between the UIL and IL leg; **– $p\geq 0.001$ comparing values between UIL vs IL leg at -15°, 0°, 15° ankle angles; # – $p<0.05$ comparing muscle MVC torque values over time in UIL and IL legs.

The plantar flexion and dorsiflexion muscle MVC torque or RFD data at a 15° ankle angle are presented in Table 4. At a **15°** ankle angle, **plantar flexion** muscle MVC torque was greater ($p<0.05$) in UIL than IL in first months in 30 ms time; after 4 months in 30 ms time; after 6 months in 30 ms, 50 ms and 200 ms time; after 10 months in 200 ms time; and after 12 months in 200 ms time.

At a **15°** ankle angle (Table 4), **dorsiflexion** muscle MVC torque was greater ($p<0.05$) in UIL than IL in the first month in 50 ms, 100 ms and 200 ms time.

Table 4. The calf muscles MVC torque of RFD at 15° ankle angle

Month	RFD (ms)	Plantar flexion		Dorsiflexion	
		UIL (Nm)	IL (Nm)	UIL (Nm)	IL (Nm)
1	30	8.3±2.4*	5.1±1.9	11.9±2.4	8.9±5.7
	50	11.5±5.1	7.2±2.5	14.2±0.8*	11.2±4.9
	100	16.7±9.6	15.4±6.9	20.6±1.2*	15.6±5.4
	200	30.5±8.6	21.5±8.8	30.4±2.4*	21.7±7.4
2	30	9.5±2.7	8.3±4.5	14.2±2.09	10.8±2.8
	50	13.2±3.3#	10.5±5.3	15.03±0.9	15.5±2.4
	100	22.3±4.4	17.8±8.3	21.6±2.3	22.3±2.9
	200	37.6±4.3	30.7±11.4#	31.13±4.0	30.8±1.5
4	30	9.9±2.8*	7.6±3.2	14.7±2.1	11.7±2.4
	50	12.8±2.8	11.2±2.9	15.9±1.9	15.8±1.6
	100	29.6±4.2	22±5.1	23.6±1.9	22.9±2.3
	200	42.1±2.9	26.1±6.5	33.1±3.3	32.9±3.6#
6	30	12.5±4.7*	8.8±3.8	13.9±3.2	11.2±2.8
	50	16.1±4.0*#	12.9±3.4	18.2±3.2	14.9±1.7
	100	25.7±6.6	23.9±6.4	26.2±5.4	19.8±4.2
	200	40.8±5.2*	33.4±0.7#	36.2±8.9	28.7±3.6
8	30	8.8±1.6	6.4±2.3	11.9±3.9	11.2±0.9
	50	12.2±1.4	7.9±2.1	16.7±2.8#	11.4±1
	100	18.6±1.3	13.8±2	21.5±2.5#	17.8±2.8
	200	28.8±1.4	26.9±4.4	27.9±2.4	24.2±5.8

Continued Table 4

10	30	9.6±1.2	7.3±2.9	13.4±2.6	12.5±0.8#
	50	12.2±0.6	10.6±2.9	17.4±1.6#	12.4±1.8
	100	18.8±2.5	16.4±3.1	21.1±1.1#	17.8±1.1
	200	33.3±4.1*	27.2±3.01	28.9±1.8	27.89±1.6
12	30	11.2±1.3#	8.3±3.4	13.3±1.9	12.2±0.7#
	50	13.6±0.6#	9.6±3.6	16.4±1.5#	14.3±1.2#
	100	21.1±2.7	13.8±4.3	22.3±1.4#	18.7±2.1
	200	38.3±2.4*	28.03±7.3	31.6±1.9	27.9±0.7

Observations: Data are shown as mean±standard deviation; UIL – non-injured leg; IL – injured leg; *– $p<0.05$, differences between the UIL and IL leg; **– $p \geq 0.001$ comparing values between UIL vs IL leg at -15°, 0°, 15° ankle angles; # – $p<0.05$ comparing muscle MVC torque values over time in UIL and IL legs

Discussion

This study was conducted to test whether the biomechanical and neuromechanical changes of plantar and dorsiflexion muscle contractile function were different between limbs of subjects who had sustained a unilateral ATR surgery in the first post-surgery year. The present study results show that over one year of unilateral ATR surgery, (1) plantar flexion muscle isometric MVC and RFD torque, and dorsiflexion muscle isometric MVC and RFD torque increased in UIL and IL, however differences remain between (2) UIL and IL and in calf muscle isometric MVC and RFD torque.

We studied calf muscle isometric MVC torque to understand the remaining functional deficits in 12 months' post-surgery period, following subjects after unilateral ATR surgery. We expected that over one-year period after unilateral ATR surgery, the calf muscle isometric MVC torque would remain greater in non-injured than injured leg. In this study we established that over one-year period after unilateral ATR surgery, isometric (Table 1) MVC torque of non-injured and injured legs increased, but after 12 months, calf muscle MVC torque differences between legs remained.

The isometric MVC torque of PF muscles was greater at ankle angles of -15º (1, 2, and 6 months), 0º (2, 4, 6, 10, and 12 months) and 15º (6, 10, and 12 months) in the UIL compared with the IL. Also the isometric torque of DF muscles was greater at ankle angles of -15º (2, 6, 8, 10, and 12 months), 0º (1, 2, 6, and 8 months) and 15º (1, 2, 6, and 8 months) in the UIL compared with the IL.

It is well known that limited physical activity as well as prolonged bed rest influences decreased muscle strength and skeletal muscle atrophy emerges (Horstamann et al., 2012; Kawakami et al., 2001). Atrophy is well pronounced in lower limb muscles and the decreases after inactivity or bed rest can be greater for strength than for muscle size (Kawakami et al., 2001). Literature contains evidence that the calf muscle atrophy after ATR surgery with the prolonged immobilization (Lantto et al., 2015; Horstamann et al., 2012; Akizuki, Gartman, Nisonson, Ben-Avi, & McHugh, 2001) causes selective atrophy of Type-I muscle fibres (Horstamann et al., 2012; Langberg, Rosendal, & Kjaer, 2007; Kawakami et al., 2001). The difference in calf muscle size can be ranged from 4.3 mm to 8 mm in injured compared to non-injured leg (Naim et al, Şimşek, Sĭpahĭoĝlu, Esen, & Cakmak, 2005). Furthermore, MVC torque differences between the IL and UIL remained for more than 2 years (Horstmann et al., 2012; Don et al., 2007) In this study we established the greater non-injured than injured leg plantar flexion and dorsiflexion muscle isometric (Table 1) torque one-year after unilateral ATR surgery.

Part of the PT programme consisted in eccentric (EE) muscles strengthening exercises. It is established that 6 weeks of eccentric muscle-strengthening exercises increase concentric and eccentric muscle strength (Kaminski, Wabbersen, & Murphy, 1998). It is also well established that 4-6 weeks of exercises influence muscle structural changes (Holtermann et al., 2007), and that 8 weeks of EE may influence muscle hypertrophy (Duclay, Martin, Duclay, Cometti, & Pousson, 2009) and lead to greater muscle strength (Farthing & Chilibeck, 2003). The gastrocnemius medialis and lateralis can perform 90% of the total MVC force during the PF movement (Arnold, Hamner, Seth, Millard, & Delp, 2013). It may be that the isometric MVC torque of the UIL and IL muscles increased because of the muscles-strengthening exercises.

The rate of force development (RFD) is determined as the slope of the force/time curve (Wang et al., 2013; Gruber & Gollhofer, 2004) thus it is important to assess the explosive strength qualities of the neuromuscular system. The ability to generate a high muscular strength within a short period is of functional importance for active joint stabilization (Gruber & Gollhofer, 2004). The RFD of plantar flexion muscles was greater at ankle angles of -15º (30, 50, 100, and 200 ms), 0º (200 ms) and 15º (30, 50, and 200 ms) in the UIL compared with the IL. The RFD of dorsiflexion muscles was greater at ankle angles of -15º (30, 50, and 200 ms), 0º (30, 50, 100, and 200 ms) and 15º (50 and 100 ms) in the UIL compared with the IL. Numerous studies have shown that ATR surgery influences ankle joint range of motion, muscle activity and strength (Finni et al., 2006; Don et al., 2007; Horstmann et al., 2012) also body balance (Wang et al., 2013; Gruber & Gollhofer, 2004) all of which lead to changed normal gait patterns. These differences between the UIL and IL may be caused by postoperative immobilization, restriction, and lower neuromuscular control capacity. Moreover, changes in gait patterns may lead to a less symmetrical loading of the lower extremities, thus potentially increasing the risk of placing higher loads on the injured side (Kongsgaard et al., 2005).

The force produced by a muscle during voluntary contraction depends on the number of active motor units, the rate of which discharge actions (Maffiuletti et al., 2016) and maximal strength of muscles (Mirkov, Nedeljkovic, Milanovic, & Jaric, 2004). Some authors suggest that factors influencing muscle MVC may also influence RFD (Maffiuletti et al., 2016; Andersen & Aagaard, 2006). Moreover, it is established that RFD depends of the tendon stiffness (Maffiuletti et al., 2016; Wang et al., 2013). Tissue stiffness is inversely proportional to length, i.e. longer tendon tissues determine slower force transmission (Maffiuletti et al., 2016; Wang et al., 2013; Bojsen-Moller, Magnusson, Rasmussen, Kjaer, & Aagaard, 2005). Moreover, muscle-tendon stiffness is more related with the late-phase RFD (150-200 ms) (Hannah & Folland, 2015), while agonistic muscle electromyography activity is an important contributor to the force through the entire initial phase (25-75 ms) (Maffiuletti et al., 2016). Wang et al. (2013) investigated the plantar flexors muscle RFD of the subjects one year after ATR surgery. The authors established greater plantar flexion muscle RFD in injured than in non-injured legs. In our study, one year after unilateral ATR surgery, we established greater calf muscle RFD (Tables 2, 3, 4) in non-injured than in injured legs. The impaired feedback control (which occurred after Achilles tendon rupture) in sensory information influenced the slower maximum rates of muscle force development for injured than for uninjured leg.

In this study, we established that the RFD of PF muscles was increased in the UIL at ankle angles of 15° (2, 6, and 12 months) in the IL at 15° (2 and 6 months) ankle angles. RFD of DF muscles was increased in the UIL at ankle angles of -15° (12 months), 0° (10 and 12 months) and 15° (8, 10, and 12 months); in the IL at 0° (10 and 12 months) and 15° (4, 10, and 12 months) ankle angles. RFD is related to the discharge rate of the motor units recruited, to alterations in the characteristics of the units recruited or to a combination of both (Gruber & Gollhofer, 2004). It is determined that during the tendon injury, the mechanoreceptors are disrupted (Kaminski et al., 1998) and that leads to altered neural or mechanical transduction in the muscle–tendon unit (Wang et al., 2013). It is also well established that sensorimotor and muscle strength exercises are basically related to RFD (Don et al., 2007; Aagaard et al., 2002). Heavy load strength training increases muscle mass, muscle activation and RFD in individuals after long-term disuse and surgery of the limb (Heggeldun et al., 2013; Holtermann et al., 2007; Suetta et al., 2004). It is established that muscle structural changes can occur after 4-6 weeks of resistance training (Blazecivh et al., 2009; Holtermann et al., 2007). There is evidence that 6 weeks of lower limb strength training increases RFD values by 33% (Vila-Cha, Falla, & Farina, 2010). Aagaard et al., (2002) established that 14 weeks of resistance strength training leads to the predominance of type II fibres, which results in a higher RFD. The maximal muscle force that can be reached in a situation of limited contraction time (<250 ms) is positively related to the proportion of type II and type III fibres (Holtermann et al., 2007; Aagaard et al., 2002). In our study, all subjects with ATR underwent an 8 weeks' physiotherapy programme, which consisted of muscle-strengthening exercises. It has been suggested that increase in neural drive, selective type II muscle fibre hypertrophy (Andersen et al., 2009), changes in the rate of muscle activation and tendon stiffness properties (Blazecivh et al., 2009) may be a causal adaptation strength training mechanism. Increase in absolute RFD implies a decrease in the time to develop a specific level of force output (Wang et al., 2013) and allows to reach a higher level of muscle force in the early phase of muscle contractions (Aagaard et al., 2002) as well as enhance maximal force generation (Holtermann et al., 2007). An increased RFD induced by muscle training allows the increase in the maximal force that can be achieved during rapid movement.

Based on the findings of this study, our suggestion is to provide supplemental exercise prescription (i.e. more sensorimotor training) in physiotherapy protocols, also to investigate whether the early rehabilitation protocol with the integrated exercises would eliminate or minimize the observed deficits in our study.

Conclusions

Over the first year after unilateral Achilles tendon surgery, the (1) plantar and dorsiflexion muscle isometric MVC torque and RFD increases in non-injured and injured legs. Differences (2) in the isometric MVC and RFD parameters of bilateral triceps surae muscle between the non-injured and injured leg in subjects with Achilles tendon repair were found within one year after unilateral ATR surgery.

Conflict of Interest: The authors have no conflicts of interest to disclose.

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DEFICITS OF CALF MUSCLES STRENGTH AND RATE OF FORCE DEVELOPMENT AFTER ACHILLES TENDON RUPTURE

Summary

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Calf muscles are important for the daily and high performance activities. Looking from the calf muscle contribution to the mechanical energetics of walking, the plantar flexion muscles are the primary contributors to body support, forward progression and swing initiation in late stance, while the tibialis anterior is responsible for providing toe clearance during early swing. The ability to produce a rapid rise in contractile force during the initial phase of voluntary contraction (RFD) is vital for individuals who need to counteract sudden perturbation in postural balance. After unilateral ATR surgery the subjects have prolonged and often profound strength deficit, however the long-term prognosis is that a strength deficit of approximately 20-30% will continue to persist in injured compared to non-injured leg. We performed a longitudinal study of changes in calf muscle isometric MVC torque and RFD development after ATR repair. We sought to understand the relative contributions of the calf muscles torque during the rehabilitation process after ATR surgery.

The aims of our study were: (1) to estimate the isometric MVC torque and RFD changes during plantar flexion and dorsiflexion and (2) to estimate the isometric MVC torque and RFD parameters during plantar flexion and dorsiflexion movements in the injured and non-injured legs at the 1-year follow-up after ATR surgery.

Methods. Eight men who underwent ATR surgery and not less than 10 rehabilitation sessions were included. The subjects performed isometric plantar flexion and dorsiflexion movements at -15°, 0°, and 15°, and the MVC torque of RFD at 30 ms, 50 ms, 100 ms and 200 ms. Each participant performed 5 ankle flexion and extension repetitions. Isometric MVC torque and RFD were measured during plantar flexion and dorsiflexion 7 times over a 1-year period.

Results. The PF muscles isometric MVC torque increased with time ($p<0.05$) in the non-injured (-15°, 0° ankle angles) leg and in the injured leg (-15° ankle angle), as well as DF muscles isometric MVC torque increased ($p<0.05$) in the injured leg (-15° ankle angle). The PF muscles RFD increased with time ($p<0.05$) in the non-injured leg (15° ankle angle) as well as DF muscles RFD increased ($p<0.05$) in the non-injured leg (-15°, 0°, 15° ankle angles) and in the injured leg (0°, 15° ankle angles). After one year isometric MVC torque and RFD during PF and DF remained greater ($p<0.05$) in the non-injured leg than in the injured leg.

Conclutions. Over the first year after unilateral Achilles tendon surgery, the (1) PF and DF muscle isometric MVC torque and RFD increases in non-injured and injured legs. One year after Achilles tendon surgery, (2) calf muscle isometric MVC torque and RFD differences were observed between non-injured and injured legs.

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