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Paretic Muscle Atrophy and Non-Contractile Tissue Content in Individual Muscles of the Post-Stroke Lower Extremity

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Abstract

Muscle atrophy is one of many factors contributing to post-stroke hemiparetic weakness. Since muscle force is a function of muscle size, the amount of muscle atrophy an individual muscle undergoes has implications for its overall force-generating capability post-stroke. In this study, post-stroke atrophy was determined bilaterally in fifteen leg muscles with volumes quantified using magnetic resonance imaging (MRI). All muscle volumes were adjusted to exclude non-contractile tissue content, and muscle atrophy was quantified by comparing the volumes between paretic and non-paretic sides. Non-contractile tissue or intramuscular fat was calculated by determining the amount of tissue excluded from the muscle volume measurement. With the exception of the gracilis, all individual paretic muscles examined had smaller volumes in the non-paretic side. The average decrease in volume for these paretic muscles was 23%. The gracilis volume, on the other hand, was approximately 11% larger on the paretic side. The amount of non-contractile tissue was higher in all paretic muscles except the gracilis, where no difference was observed between sides. To compensate for paretic plantar flexor weakness, one idea might be that use of the paretic gracilis actually causes the muscle to increase in size and not develop intramuscular fat. By eliminating non-contractile tissue from our volume calculations, we have presented volume data that more appropriately represents force-generating muscle tissue. Non-uniform muscle atrophy was observed across muscles and may provide important clues when assessing the effect of muscle atrophy on post-stroke gait.

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There are no conflicts of interest.

Keywords

stroke; hemiparesis; magnetic resonance imaging (MRI); muscle volume; non-contractile tissue

Introduction

Stroke is the third leading cause of death in the United States and a leading cause of long-term disability (NCHS, 2010). Following stroke, motor neurons and signaling pathways of the central nervous system are damaged, leaving the person with a variety of disabilities including impaired speech and cognitive difficulties (NINDS, 2009). Most commonly observed is hemiparesis, or muscle weakness contralateral to the brain lesion (Chan, 1986; Andrews and Bohannon, 2000). Immediately following stroke, walking is limited in two out of three patients (Jorgensen et al., 1995). When ambulation ability is regained, post-stroke gait is typically characterized by a number of spatio-temporal, kinematic, and kinetic deficits compared to normal gait (Olney and Richards, 1996) such as asymmetric stance periods (Brandstater et al., 1983; Wall and Turnbull, 1986; Olney et al., 1994; Olney and Richards, 1996), decreased walking speeds (Brandstater et al., 1983; Burdett et al., 1988; Olney et al., 1994; Turnbull et al., 1995; von Schroeder et al., 1995; Witte and Carlsson, 1997), and decreased center of mass support (Higginson et al., 2006). Walking performance after stroke is related to paretic knee extensor strength (Hamrin et al., 1982; Nakamura et al., 1985, 1988; Bohannon 1989a,b; Bohannon and Andrews, 1990; Bohannon and Walsh, 1992) and slow gait speed is associated with reduced joint moment and power produced at the ankle by the plantar flexors (Olney et al. 1991, 1994; Nadeau et al., 1999). Consequently, determining the factors underlying muscle weakness will increase our understanding of post-stroke gait and facilitate the design of therapeutic interventions.

Post-stroke hemiparesis is dependent upon a combination of neurological, mechanical, and structural factors (Patten et al., 2004). A decrease in the ability to activate individual motor units, a loss of functioning motor units (McComas et al., 1973), and a reduction in the firing rates for each motor unit (Rosenfalck and Andreassen, 1980; Tang and Rymer, 1981) can contribute to post-stroke muscle weakness. Muscle properties like specific tension, force-length or force-velocity relationships, and fiber type also change with varying levels of use and disuse (Edgerton, 1978; Salmons and Henriksson, 1981; Lieber 1986; Kawakami et al., 1995) and may also contribute to post-stroke strength deficits. Additionally, post-stroke hemiparesis may be exacerbated by disuse atrophy (McComas, 1994).

Skeletal muscles can change in size with increased and decreased levels of use (Jones and Rutherford, 1987; Leblanc et al., 1988), and the physiological cross-sectional area of a muscle is proportional to its overall force-generating capability (Maughan et al., 1983; Powell et al., 1984; Brand et al., 1986; Narici et al., 1992; Roy and Edgerton, 1992; Lieber, 2010). Therefore, the amount of post-stroke atrophy a muscle or group of muscles undergoes is important in properly describing any changes to the overall ability to generate force. The amount of non-contractile tissue in a muscle, especially intramuscular fat, increases with age and some diseases (Mitsiopoulos et al., 1998). Following a neurological impairment, muscle fibers may be lost and replaced with fat and fibrous tissues if the denervation is not exceeded by reinnervation of the remaining muscle fibers. This phenomenon commonly occurs during normal aging of human muscle (Lexell et al. 1988; Porter et al., 1995) and may be an additional factor to consider when describing post-stroke muscle changes. The loss of active muscle fibers and the substitution of non-contractile tissue will result in a change in the mechanical properties (e.g. stiffness) of post-stroke muscles and their overall force-generating capacity.

Studies using imaging techniques such as dual-energy X-ray absorptiometry (DEXA) (Iversen et al., 1989; Jorgensen and Jacobsen, 2001) and computed tomography (CT) (Sunnerhagen et al. 1999; Ryan et al., 2002; Metoki et al., 2003) have confirmed muscle atrophy in post-stroke limbs. Iversen et al. (1989) and Jorgensen and Jacobsen (2001) noted a decrease in paretic muscle mass and an increase in paretic fat mass using DEXA. Ryan et al. (2002) reported that overall paretic mid-thigh muscle area was 20% lower than non-paretic area, and subcutaneous fat content was higher on the paretic side. Metoki et al. (2003) measured thigh muscle volume in stroke patients using CT and found a decrease in muscle volume on the affected side. While these studies describe muscle atrophy that occurs post-stroke, they are limited to atrophy of specific cross-sections of the leg and atrophy in entire limbs or muscle groups such as the thigh. The extent of muscle atrophy observed in each individual muscle has not been reported. In addition, both of these imaging methods expose the patient to radiation and may not be favorable to the subject (Eng et al., 2007), and DEXA is sensitive to body hydration levels (Pietrobelli et al., 1998).

Magnetic resonance imaging (MRI) is advantageous in measuring skeletal muscle variations because it overcomes the aforementioned limitations of DEXA and CT (Murphy et al., 1986). Recent studies have used MR imaging methods to measure changes in muscle volume in young healthy adults (Holzbaur et al., 2007), people with anterior cruciate ligament (ACL) deficiencies (Williams et al., 2005a,b), and youths with cerebral palsy (Lampe et al., 2006). When comparing different muscles in patients pre and post ACL reconstruction, non-uniformities in atrophy were reported (Williams et al., 2004), implying that different leg muscles lose their force-generating capacities at different rates. In neurologically impaired patients, Lampe et al. (2006) found that the paretic side of young adults with cerebral palsy had decreased muscle volume. Similarly, Ploutz-Snyder et al. (2006) used MRI to measure the changes in cross-sectional area that occur in the post-stroke upper extremity. These studies were able to isolate individual muscles and calculate individual muscle volumes, rather than entire muscle groups.

The purpose of this study was to calculate muscle volumes for paretic and non-paretic limbs and determine individual muscle atrophy. We hypothesized that paretic muscle volumes would be significantly smaller than non-paretic muscle volumes and that non-contractile tissue content would be higher in paretic muscles. The change in force-producing capacity is directly related to muscle atrophy and non-contractile tissue development, and may have implications for muscle function and the response to rehabilitation strategies in post-stroke gait.

Methods

Subjects

Eleven subjects with post-stroke hemiparesis (mean age 61.9 ± 8.0 years, 46 ± 38 months since stroke) participated in the study. Lower-extremity Fugl-Meyer scores ranged from 12–26, which is comparable to previously reported scores found in studies investigating walking in persons living with chronic stroke (Chen et al., 2005; Plummer et al., 2007; Sullivan et al., 2007). A complete summary of subject demographics can be found in Table 1. Inclusion criteria were (1) chronic stroke occurring at least six months previously; (2) single lesion; (3) age 30–80 years; and (4) ambulatory but with noticeable gait deficits. Subjects were excluded if they had (1) multiple strokes affecting both sides of the body; (2) heart disease or hypertension; (3) dementia; (4) severe aphasia; (5) orthopedic or pain conditions; (6) cancer; (7) any metal implants; or were (8) claustrophobic. The study was approved by the University of Delaware Review Board. Prior to participation, all patients provided their written informed consent.

Imaging

Patients lay supine in a 1.5T Signa LX scanner (GE Medical, Milwaukee, WI) with their feet taped at the toes to limit any movement during the scan period and maintain neutral hip rotation. Axial spin-echo T1-weighted MR images were acquired of both legs simultaneously from the ankle mortise to the iliac crest using the scanner's body coil. Images were taken in five overlapping sequences: ankle, lower leg, knee, thigh, and pelvis. A repetition time (TR) of 450 ms, echo time (TE) of 10 ms, slice thickness of 10 mm and space between slices of 11.5 mm (center to center) was used for all scanned region except for the knee region (slice thickness of 5 mm and space between slices of 6 mm). A matrix size of 256×256 and field of view of 400 mm were used for all scans.

Muscle Volume Reconstruction

Each muscle was digitally reconstructed by tracing the muscle boundary (Figure 1a) over the entire length of the muscle belly. Fifteen muscles were traced for each leg: soleus (SOL), medial gastrocnemius (MG), lateral gastrocnemius (LG), tibialis anterior (TA), biceps femoris-short head (BFS), biceps femoris-long head (BFL), semimembranosus (SM), semitendinosus (ST), gracilis (GRA), sartorius (SAR), rectus femoris (RF), vastus medialis (VM), vastus intermedius (VI), vastus lateralis (VL), and tensor fasciae latae (TFL).

Prior to measuring muscle volumes, a validation study comparing a rectangular cube calibration phantom ($15.0 \text{ cm} \times 14.8 \text{ cm} \times 37.2 \text{ cm}$; 8258.4 cm^3) to the measured reconstructed volume was performed; all measured volumes were within 1% of the phantom volume. A single observer manually traced the images of all subjects using a digitization tablet (Cintiq 18SX, Wacom Technology Corp., Vancouver, WA) and IMOD software (University of Colorado, Boulder, CO) (Kremer et al., 1996). All digitization was performed by a single rater, and intraobserver reliability was established in a test-retest reliability study for three muscles (SOL, MG, SAR) of one subject for both the paretic and non-paretic sides (paretic correlation coefficient = 0.999; non-paretic correlation coefficient = 0.994). A minimum of one month between tracings elapsed to reduce any memory bias from the observer. Subject-specific triangle-based surface mesh models (Figure 2) for each muscle were built using Nuages software (Nuages, INRIA, Sophia-Antipolis, France) (Geiger, 1993). Unadjusted muscle volumes (Table 2) were calculated from the surface mesh models using subroutines from the Visualization Toolkit (Kitware Inc., Clifton Park, NY) (Schroeder et al., 1997).

To describe the actual contractile tissue more precisely, proximal and distal tendons were excluded and non-contractile tissue content was eliminated. To eliminate non-contractile tissue from the net muscle volume calculation, a pixel threshold was determined for each subject by visually inspecting each MRI scan for fatty regions, which are white areas on the image. Pixel thresholds were consistent for both paretic and non-paretic legs. Other studies have used similar grey-level (pixel-intensity) methods to distinguish between lean skeletal muscle and adipose tissue (Ross et al., 1996; Kent-Braun et al., 2000; Goodpaster et al., 2004). Cross-sectional areas were calculated using a trapezoidal integration algorithm, then adjusted for non-contractile tissue content by removing the pixels below the specified threshold that represented fat and other tissue (Figure 1b). The adjusted cross-sectional areas were then summed over the length of each muscle, and multiplied by the slice thickness to obtain adjusted muscle volumes. Overlapping images from adjacent scan regions (e.g. pelvis region images overlap thigh scan region) and muscles that crossed the knee (e.g. MG and LG) which had different slice thicknesses were accounted for in the adjusted volume calculation. Non-contractile tissue content for each individual muscle was determined by comparing the net muscle volume with the adjusted muscle volume and calculating a percent difference between the two values.

All reported muscle volumes were adjusted for non-contractile tissue content. While it is likely that both paretic and non-paretic limbs have changed in comparison to the subjects' pre-stroke condition, muscle volumes from that time are unknown. Therefore, we defined muscle atrophy as the relative difference between paretic and non-paretic limbs for each muscle. A negative percent difference represents a volume reduction on the paretic side, and a positive value represents a reduction on the non-paretic side. An average percent difference was calculated for all muscles that had lower volumes on the paretic side. One-tailed paired t-tests ($\alpha=0.05$) were used to test for significant differences between paretic and non-paretic muscle volumes for each individual muscle.

Results

All muscle volumes were lower on the paretic side when compared to the non-paretic side, except the GRA (Table 3). Significant differences between the paretic and non-paretic sides were observed for all muscles except the TA ($p=0.2647$), SM ($p=0.0974$), and GRA ($p=0.1074$). The TA was affected the least with a percent difference of 4%, and the largest percent difference occurred in the TFL, with a 51% difference. The mean change in individual muscle volume for the fourteen muscles with smaller paretic volumes was 23%. In the shank region the average decrease in individual muscle volume was 20%. Likewise in the thigh region, the average decrease was 24%. The GRA muscle was the only muscle that showed an increase in muscle volume on the paretic side, with a non-significant average increase of 11% relative to the non-paretic side.

The amount of non-contractile tissue was higher in all paretic muscles except the gracilis (Table 4). The paretic SM had the highest percentage of fat (48%), and the non-paretic RF had the lowest percentage of fat (5.3%). Comparing between paretic and non-paretic fat percentages, the TFL had the highest percent difference of fat (55%) and the GRA showed zero difference.

Discussion

In this study we have presented post-stroke muscle volumes for fifteen muscles from both paretic and non-paretic legs. MR imaging and digital reconstruction techniques allowed us to isolate each individual muscle, adjust non-contractile tissue, and quantify muscle atrophy by comparing volumes between limbs. We found that all paretic muscles were significantly smaller ($p<0.05$) except the TA, SM, and GRA, with similar magnitude differences in both the shank and thigh regions. The percentage of non-contractile tissue was higher in all the paretic muscles.

These results are similar to other studies that measured muscle atrophy using imaging techniques (Ryan et al., 2002; Metoki et al., 2003; Lampe et al., 2006) and confirm that muscle atrophy does occur in individual muscles post-stroke, albeit not in a uniform manner. Post-stroke cross-sectional areas have been reported to decrease an average of 20% in the paretic thigh (Ryan et al., 2002), and depending on age, thigh muscle volumes ranged between 17–25% smaller when paretic thighs were compared to non-paretic (Metoki et al., 2003). Our paretic thigh volumes were 24% smaller than the non-paretic thigh. Metoki et al. (2003) measured thigh volume in a predetermined region of the thigh, and likely excluded portions of individual muscles in their calculation. We calculated muscle volumes over the entire length of the muscle belly, which may explain why our differences were slightly higher. Neither of the previous studies measured shank volume changes in post-stroke individuals, so we were unable to compare our results directly to other post-stroke data.

The amount of non-contractile tissue and specifically intramuscular fat content increases with age, obesity, and various diseases (Mitsopoulos et al., 1998). Although Ramnemark et al. (1999) did not find any significant changes between paretic and non-paretic legs following stroke, some studies have (Iversen et al., 1989; Jorgensen and Jacobsen, 2001). Post-stroke intramuscular fat mass has been reported to increase in the paretic arm and leg by approximately 15% and 8%, respectively (Iversen et al., 1989). Our results show that for this cohort of subjects, all paretic muscles besides the gracilis have more non-contractile tissue than non-paretic muscles. While we report non-contractile tissue content and changes to muscle volumes as a result, our method for determining fat content from MRI has not been validated. A recent technique involving iterative decomposition of water and fat with echo asymmetry and least squares estimation (IDEAL) has been reported to be a more reliable method for estimating fat content in MR imaging (Reeder et al., 2005). A comparison between our method for fat-suppression and IDEAL may be necessary for proper validation. Although pixel thresholds set for each subject may not be exact measures of fat content, the same value is used for both limbs and any error would be similar for both sides and tend to cancel. We feel that the amount of muscle atrophy and its effect on a muscle's force-generating capability are more appropriately represented when accounting for non-contractile tissue.

The percent difference between the paretic and non-paretic soleus is 12% which is much less than the atrophy observed in the remaining plantar flexors (medial gastrocnemius, 38%, and lateral gastrocnemius, 26%). This difference between muscles suggests that the gastrocnemius atrophies preferentially in the plantar flexor group. The soleus and gastrocnemius each have specific roles for forward propulsion and vertical support during normal gait (Neptune et al., 2001), and plantar flexor weakness has been noted as a limiting factor in post-stroke gait speed (Nadeau et al., 1999). Since the gastrocnemius contributes to swing initiation and atrophies preferentially over the soleus, our results imply that atrophy of the gastrocnemius plays a key role in limiting swing initiation in post-stroke subjects. This implication has not been thoroughly studied; however, it may be possible with the recent development of musculoskeletal modeling software such as OpenSim (Delp et al., 2007).

Another surprising result was the gracilis was larger on the paretic side rather than the non-paretic. We hypothesized that all muscles on the paretic side would be significantly lower than their non-paretic counterparts. In the case of the gracilis, this hypothesis was not supported. Since the gracilis is a relatively small knee flexor, an 11% average increase in muscle volume observed on the paretic side may not be clinically relevant in regards to the contribution of the gracilis to knee flexion function. However, the gracilis acts not only as a knee flexor, but also as a hip flexor and hip adductor. Our study was limited in that the focus was on muscles crossing the knee and ankle joints, and therefore we did not investigate muscle volume changes in other hip flexors and adductors. Nadeau et al. (1999) reported that post-stroke subjects may compensate for paretic plantar flexor weakness with ipsilateral hip flexors. It is therefore possible that paretic hip flexor muscles such as the gracilis will actually increase in size as a result of increased use as they compensate for plantar flexor weakness during gait.

Our results also show that the tibialis anterior muscle volume is not significantly lower on the paretic side, with only a 4% difference between sides. We also found that the paretic and non-paretic dorsiflexors had similar amounts of non-contractile tissue, each with less than 10%. Therefore, with similar muscle volumes and intramuscular fat content between sides, we determined that the tibialis anterior atrophied the same amount per side following stroke. During normal gait, the primary function of the tibialis anterior muscle is to lift the foot clear of the ground and control plantar flexion after heel strike (Burrage et al., 2001). However, post-stroke gait deficits such as foot drop during swing (Burrage et al., 2007) and

limited ankle dorsiflexion at initial contact and during stance are often attributed to dorsiflexor muscle weakness (Olney and Richards 1996) – specifically the tibialis anterior muscle (Burridge et al., 2007). Since both the paretic and non-paretic tibialis anterior muscles atrophied the same amount, our findings suggest that greater muscle weakness on the paretic side must be attributed to impaired activation rather than muscle atrophy.

In this study, we have provided average muscle volumes for subjects with post-stroke hemiparesis. If one assumes a constant pennation angle and optimal fiber length, the change in physiological cross-sectional area (PCSA) is equal to the change in muscle volume (Roy and Edgerton, 1992). Using this relationship and further assuming that muscle specific tension remains uniform after stroke, the percent change in PCSA directly reflects the change in muscle force capacity. The validity of these assumptions have not been verified and warrant further study. Since muscle volume is a determinant of PCSA, these data can be used in the future to study the effect muscle atrophy has on PCSA and each individual muscle's force-generating capability for both paretic and non-paretic legs.

There were several limitations inherent in this study. First, we had a limited number of participants, with a wide range of time between their onset of stroke and MRI date. Additionally, subjects were included if they were ambulatory but with noticeable gait deficits; however, the history of physical rehabilitation is unknown. Previous rehabilitation may alter the results if there was emphasis placed on increasing the strength and size of the paretic limb. We feel that by including a wide variety of subjects, our subject pool is still representative of the general stroke population. Another limitation is that the slice thickness is on the high end for proper volume resolution using MRI. By decreasing the slice thickness, our estimations of both muscle and fat tissue might be more accurate because the voxel size would be lower and the resolution would be higher. Decreasing the slice thickness would also minimize the error introduced due to any discrepancies in muscle boundary tracings, and thus cross-sectional areas, between overlapping image regions. Validation of our method using a phantom without accounting for the amount of fat mass may also limit our study in that fat density may not be uniform and can change over time. Our study was also limited by including muscles only at the knee and ankle. Post-stroke subjects that utilize hip strategies (e.g. hip hiking, hip vaulting, circumduction) to compensate for lower leg muscle weakness may in fact be preventing atrophy of major hip muscles.

To our knowledge no prior study has investigated muscle atrophy in individual lower extremity muscles following stroke, and there have been no reported values for post-stroke individual muscle volumes. Our study confirmed muscle atrophy in the paretic leg in all but three muscles of the knee and ankle, and showed that intramuscular fat or non-contractile tissue is greater on the paretic side. By eliminating intramuscular fat from our volume calculations, we have presented volume data that represents the true force-generating muscle tissue that may be used in future studies to assess the effect of muscle atrophy on post-stroke gait.

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Figure 1.

(a) MR image of both paretic (L) and non-parietic (R) limbs with muscle boundaries located and labeled for three muscles of the shank region. (b) Same MR image as (a) with non-contractile tissue pixels removed. Pixels representing muscle tissue retain their respective colors and are included in the adjusted volume calculation. For both limbs, the medial gastrocnemius (MG) is in blue, lateral gastrocnemius (LG) is in red, and soleus (SOL) is in green.

Figure 2.
(a) Muscle boundaries for consecutive MR images of one muscle over the entire length of the muscle belly and (b) the triangle-based surface mesh model generated by Nuages software.

Table 1
Subject demographics and clinical assessment scores for 11 post-stroke hemiparetic individuals.

Clinical Characteristics of Participants							
Patient	Age (yr)	Gender	Body Mass (kg)	BMI	Time Since Stroke (months)	Side of Hemiparesis	Fugl-Meyer Lower Extremity Motor Score
1	66	Female	73.2	26.9	24	R	22
2	58	Male	77.8	25.7	12	R	13
3	47	Male	69.5	21.4	15	R	15
4	65	Female	78.9	29.9	22	R	18
5	52	Male	87.2	25.4	120	L	22
6	55	Male	102.0	31.4	85	L	26
7	68	Male	86.0	28.0	40	L	19
8	60	Male	119.1	37.7	18	L	18
9	62	Male	73.1	22.5	77	R	25
10	73	Male	94.1	27.0	82	R	12
11	70	Female	93.7	35.5	9	L	26

Table 2

Individual muscle volumes without using pixel threshold for non-contractile tissue adjustment and percent differences between paretic and non-paretic sides.

Individual Muscle Volumes without Non-Contractile Tissue Adjustment			
	Paretic±SD (cm ³)	Non-Paretic±SD (cm ³)	% Difference
SOL	411.71±113.09	424.45±107.04	-3
MG	189.51±45.94	227.23±63.84	-17
LG	142.88±53.12	164.15±48.44	-13
TA	120.10±42.33	123.23±33.52	-3
<i>Shank Average</i>			-9%
BFS	72.30±29.00	82.38±33.81	-12
SM	219.82±78.42	222.15±69.38	-1
ST	158.05±39.69	196.98±60.22	-20
BFL	163.92±47.03	178.83±45.56	-8
GRA	100.94±30.42	88.54±35.51	+14
SAR	121.62±64.01	158.03±80.01	-23
RF	200.77±57.91	229.94±70.52	-13
VM	335.38±121.01	411.37±115.72	-18
VI	213.48±60.91	272.63±105.87	-22
VL	704.70±285.43	824.48±248.08	-15
TFL	48.80±17.74	73.32±20.67	-33
<i>Thigh Average</i>			-17% [†]

[†] Average volume decrease did not include the gracilis, which was larger on the paretic side.

Table 3

Individual muscle volumes using pixel threshold for non-contractile tissue adjustment, percent differences between paretic and non-paretic sides, and p values for fifteen lower extremity muscles. Significance was determined for $p < 0.05$.

Individual Muscle Volumes with Non-Contractile Tissue Adjustment				
	Paretic $\pm$ SD (cm ³)	Non-Paretic $\pm$ SD (cm ³)	% Difference	p value
SOL	281.42 $\pm$ 116.38	319.00 $\pm$ 75.70	-12	0.0490*
MG	111.82 $\pm$ 42.08	181.04 $\pm$ 56.17	-38	0.0050*
LG	104.30 $\pm$ 29.00	140.46 $\pm$ 48.78	-26	0.0007*
TA	108.60 $\pm$ 36.44	112.79 $\pm$ 26.22	-4	0.2647
<i>Shank Average</i>			-20%	
BFS	45.99 $\pm$ 21.46	64.12 $\pm$ 31.27	-28	0.0036*
SM	117.61 $\pm$ 68.47	130.10 $\pm$ 65.51	-10	0.0974
ST	139.19 $\pm$ 33.71	178.41 $\pm$ 61.34	-22	0.0059*
BFL	120.68 $\pm$ 47.97	150.89 $\pm$ 50.73	-20	0.0018*
GRA	82.38 $\pm$ 27.84	72.93 $\pm$ 32.89	+11	0.1074
SAR	86.83 $\pm$ 50.22	122.00 $\pm$ 65.78	-29	0.0011*
RF	187.21 $\pm$ 57.85	218.69 $\pm$ 69.64	-14	0.0010*
VM	278.39 $\pm$ 122.30	355.82 $\pm$ 105.59	-22	0.0026*
VI	187.08 $\pm$ 57.89	247.23 $\pm$ 100.87	-24	0.0037*
VL	598.94 $\pm$ 260.13	748.13 $\pm$ 240.56	-20	0.0001*
TFL	29.46 $\pm$ 12.56	60.07 $\pm$ 19.45	-51	<0.0001*
<i>Thigh Average</i>			-24% [†]	

[†] Average volume decrease did not include the gracilis, which was larger on the paretic side.

Table 4

Non-contractile tissue content for fifteen individual muscles represented by percentages. The difference between paretic and non-paretic non-contractile tissue content is represented by a percent difference.

Percent of Non-Contractile Tissue				
	Paretic±SD (%)	Non-Paretic±SD (%)	% Difference	p value
SOL	31.54±18.34	23.53±13.15	25	0.0154*
MG	39.55±24.20	19.52±12.68	51	0.0071*
LG	23.18±15.34	14.09±13.41	39	0.0016*
TA	8.56±7.17	7.15±8.67	16	0.4581
<i>Shank Average</i>			33%	
BFS	36.42±11.54	23.75±9.91	35	0.0010*
SM	48.01±20.52	42.44±22.26	12	0.1041
ST	11.32±7.03	10.15±6.18	10	0.6026
BFL	26.72±18.49	17.18±13.86	36	0.0313*
GRA	18.62±10.63	18.62±7.36	0	0.9990
SAR	29.29±10.25	22.81±8.82	22	0.0148*
RF	7.33±4.31	5.29±4.07	28	0.0470*
VM	18.52±10.39	13.34±8.87	28	0.0885
VI	12.79±5.54	9.69±5.15	24	0.0025*
VL	15.16±8.65	9.53±6.64	37	0.0008*
TFL	39.78±19.85	17.88±14.82	55	0.0009*
<i>Thigh Average</i>			26%	