HHS Public Access
Author manuscript
Proc SPIE Int Soc Opt Eng. Author manuscript; available in PMC 2018 April 27.

Published in final edited form as:
Proc SPIE Int Soc Opt Eng. 2018 February ; 10574: . doi:10.1117/12.2293028.

Strain Map of the Tongue in Normal and ALS Speech Patterns from Tagged and Diffusion MRI

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Abstract

Amyotrophic Lateral Sclerosis (ALS) is a neurological disease that causes death of neurons controlling muscle movements. Loss of speech and swallowing functions is a major impact due to degeneration of the tongue muscles. In speech studies using magnetic resonance (MR) techniques, diffusion tensor imaging (DTI) is used to capture internal tongue muscle fiber structures in three-dimensions (3D) in a non-invasive manner. Tagged magnetic resonance images (tMRI) are used to record tongue motion during speech. In this work, we aim to combine information obtained with both MR imaging techniques to compare the functionality characteristics of the tongue between normal and ALS subjects. We first extracted 3D motion of the tongue using tMRI from fourteen normal subjects in speech. The estimated motion sequences were then warped using diffeomorphic registration into the b0 spaces of the DTI data of two normal subjects and an ALS patient. We then constructed motion atlases by averaging all warped motion fields in each b0 space, and computed strain in the line of action along the muscle fiber directions provided by tractography. Strain in line with the fiber directions provides a quantitative map of the potential active region of the tongue during speech. Comparison between normal and ALS subjects explores the changing volume of compressing tongue tissues in speech facing the situation of muscle degradation. The proposed framework provides for the first time a dynamic map of contracting fibers in ALS speech patterns, and has the potential to provide more insight into the detrimental effects of ALS on speech.

Keywords

Tongue; ALS; speech function; atlas; motion; dynamic MRI; DTI; tractography

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1. INTRODUCTION

Amyotrophic Lateral Sclerosis (ALS) is a neurodegenerative disease when tissue in the nervous system progressively degenerates, affecting nerves controlling the movement of human body and resulting in difficulties in movement, speech, swallowing, and respiration. The average life expectancy of an ALS patient from the time of diagnosis is around two to four years and no cure for ALS is currently known[1]. In ALS, bulbar symptoms at onset are reported in about 30% of patients and almost all patients will develop bulbar problems at later stages of the disease[2]. Motoneuron loss affects patients' tongue muscles, causing structural and functional changes that lead to weakened, slowed, and limited tongue motion. Therefore, determining how an ALS tongue functions during speech has become an important topic for neurologists and speech-language pathologists to improve the diagnosis and clinical treatment of the disease. It requires a methodology to measure and analyze the tongue's internal muscular behaviors.

New techniques based on magnetic resonance imaging (MRI) have been playing an increasingly important role in the structural and functional study of the human tongue. Tagged MRI (tMRI) has been used for decades to capture the tongue's internal motion[3,4]. In tMRI, magnetic fields are artificially manipulated to produce striped "tag patterns" that deform together with the tissue in motion. In post-processing, for each time frame, tMRI slices are analyzed in post-processing steps using motion extraction algorithms such as phase-based methods[5] to produce four-dimensional (4D) motion field (3D space with time) reflecting the deformation of tissue points in the tongue[6,7]. These motion fields can be used to calculate the time-varying strain patterns of the tongue in speech to reflect local tissue activities. On the other hand, to study the internal tissue fiber structures, diffusion tensor imaging (DTI) has been widely adopted in brain MRI studies such as white matter tractography[8]. DTI reveals the diffusion process of water molecules in tissues in vivo, and the diffusion patterns reflect the microscopic details inside the tissue architecture[9]. Tractography is commonly used following DTI to reconstruct and visualize internal fibers[10]. In recent developments, DTI has been applied to the tongue region to reveal the fiber directions among the complex internal tongue muscle structures[11,12].

In current ALS speech studies, although various measurements have been investigated, internal structure and function of the tongue have not been studied due to the lack of imaging tools. In terms of tongue MRI, there have been works proposed to analyze strain in the artificial tongue muscle fiber directions, showing different speech patterns between normal subjects and post-glossectomy patients[13]. However, it is not straightforward to apply existing techniques to ALS patients especially when the symptom is severe. Since ALS symptoms have relatively fast development stages, late-stage ALS patients are likely to show severe bulbar symptoms and it is difficult for them to consistently perform speech tasks in multiple repetitions.

To address the problems described above, in this work we propose a method to compute strain in the line of action of tongue muscles with the aid of 4D motion atlases[14,15] constructed from normal subjects. Since atlases of the tongue have been a useful tool in analyzing motion in subject-specific spaces[16], they can be applied in various scenarios to provide missing information in a statistical way. In this work, although ALS patient-specific motion quantities are difficult to measure, we use a motion atlas to approximate their motion and strain during speech, while we use DTI to focus on revealing these patients' structural change in their internal muscle fibers. The tongue's motion fields in a controlled speech task were collected in advance and computed from tMRI of fourteen normal subjects. Meanwhile, DTI of two normal controls and an ALS patient were collected in another separate study and tractography was used to reveal their muscle fiber directions. For each DTI subject, the fourteen motion field sequences were deformed to its b0 space using image registration and a 4D motion field atlas was constructed to represent a statistical motion sequence. Henceforth, the strain in the line of action was computed combining the statistical motion atlas and each individual's tractography. We compared the result of the ALS patient to the two normal controls. Since strain in the line of action is an indicator of potential muscle activation in speech, the change of compressed regions in the tongue has the potential to indicate some compensation strategies applied by the patient in the case of muscle degeneration, and can be used as a quantitative representation to study the commonality and variability of an ALS patient's speech pattern.

2. METHODS

2.1 Motion estimation of tMRI

To construct a 4D motion atlas, fourteen healthy subjects participated in the first part of the acquisition, where they performed a speech task by pronouncing the utterance "a souk" in repeated speech cycles while tMRI slices were collected at a rate of 26 frames per second. The utterance was designed so that the tongue was expected to start from a neutral position /ə/, perform a forward motion at /s/, and finally arrive at an upward position at /k/ after transitioning through /u/. The subjects' motion was captured in the deformed tag patterns. We then process tMRI images with the phase vector incompressible registration algorithm (PVIRA)[7]. For each subject at each time frame, PVIRA estimates an incompressible dense 3D motion field, which we denote as $\boldsymbol{u}_{s,t}(\boldsymbol{X})$ for subject s at time frame t. Each subject yields a 4D motion sequence quantified by 26 dense 3D motion field estimates. We use $\boldsymbol{\phi}$ to denote the corresponding deformation as

$$\phi_{s,t}(\boldsymbol{X}) = \boldsymbol{X} + \boldsymbol{u}_{s,t}(\boldsymbol{X}) . \quad (1)$$

At the first undeformed time frame, $\boldsymbol{X}$ is the coordinates of the tissue points in the 3D voxel space. Note that in this work, we use a Lagrangian definition to root every motion field in the undeformed frame (material framework $\boldsymbol{X}$). In this way, no matter what quantities we compute over time, they are always mapped and displayed on the undeformed frame and the tongue appears "motionless"[15]. The reason we select the Lagrangian framework instead of Eulerian is because DTI quantities are to be acquired in a static space so that it is necessary to also use a motionless framework for the atlas to later establish a connection between the atlas space and the DTI b0 space.

We also note that since all fourteen subjects spoke at different rates during acquisition, it is necessary to temporally align the estimated motion fields. The estimation results from PVIRA have certain physical properties such as inverse-consistency and incompressibility so that it is not recommended to change the motion field estimate itself. Therefore, we manually specified the time instants of the four critical time frames /ə/, /s/, /u/, and /k/ for each subject and first align the motion fields at these four instants. Then the time indices between these critical frames are interpolated and aligned. The motion field closest to the interpolated index is mapped to that instant. In such a way, the motion fields are unaltered and time-aligned across all fourteen subjects.

2.2 Subject-specific 4D motion atlases

To reveal internal muscle fiber structures, in the second part of the acquisition, two normal controls and an ALS patient underwent DTI scans in the tongue region. The DTI data were processed and tractography was computed to reflect the fiber orientations in the tongue muscles (Figure 1), which we denote as $\boldsymbol{d}(\boldsymbol{X})$. These three DTI subjects were processed independently. For each subject, we apply diffeomorphic image registration between its static b0 space and each undeformed (first) frame of the fourteen tMRI subjects. We use ψ_s ($1 \le s \le 14$) to denote the deformation between subject s and the DTI subject's b0 space. According to [17], all subjects' motion fields are deformed into the b0 (atlas) space by

$$\phi'_{s,t} = \psi_s \circ \phi_{s,t} \circ \psi^{-1}{}_s . \quad (2)$$

Note that $\boldsymbol{\phi}'_{s,t}(\boldsymbol{X}) = \boldsymbol{X} + \boldsymbol{u}'_{s,t}(\boldsymbol{X})$, and the warped motion fields $\boldsymbol{u}'_{s,t}(\boldsymbol{X})$ in the b0 space are averaged and its mean is used as a statistical 4D motion atlas by

$$\bar{\boldsymbol{u}}_t(\boldsymbol{X}) = \frac{1}{14}\sum_s \boldsymbol{u}'_{s,t}(\boldsymbol{X}) . \quad (3)$$

The subject-specific 4D motion atlas provides a statistical way to simulate the motion of the DTI subjects by establishing a connection using diffeomorphic image registration.

2.3 Strain in the line of action for ALS

Now that motion information from tMRI is obtained, it can be matched with the diffusion data to compute strain in the line of action. In the material frame $\boldsymbol{X}$, the deformation gradient tensor is defined as

$$F_t(\boldsymbol{X}) = \frac{d\boldsymbol{x}}{d\boldsymbol{X}} = (I + \frac{d\bar{\boldsymbol{u}}_t}{d\boldsymbol{X}}) . \quad (4)$$

According to [13], strain in the line of action of muscle fibers is found at every time frame by computing the L2-norm of the projection of $F_t(\boldsymbol{X})$ to the fiber directions:

$$e_t(\boldsymbol{X}) = \|F_t(\boldsymbol{X})\boldsymbol{d}(\boldsymbol{X})\|_2 . \quad (5)$$

At each voxel, strain in the line of action $e_t(\boldsymbol{X})$ is a scalar indicating the ratio of a local deformation to its original muscle fiber length. It is also a dynamic map of the tongue muscle activities. A value less than 1 indicates shortening that could either be spontaneous muscle activation or passive compression.

3. RESULTS

4D motion atlases were constructed independently in the spaces of two normal controls and one ALS patient. In Figure 2, four critical time frames are shown for the positions of /ə/, /s/, /u/, and /k/. Note that the patient has a degenerated tongue shape that falls flat to the posterior direction and is less symmetrical from left to the right.

At each voxel, tractography results shown in Figure 1 were then imported to reveal the directions of local fibers. The local fiber directions are represented by cylinders and visualized in Figure 3. We use the same color-coding scheme as Figure 2. The fan-shaped fibers that originate from the bottom of the tongue and spread to the top and back of the tongue body are very prominent. It is a representation of the genioglossus, a major muscle that forms a majority of the internal tongue volume. Although the sizes of the tongue are difference among all three subjects, the internal fiber structures of the two controls are similar, while the patient seems to have lost many inferior-superior fibers due to muscle degeneration.

Finally, for each subject, the information from its 4D motion atlas and DTI tractography was combined and strain in the line of action was computed along these local fiber directions. We thresholded $e_t(\boldsymbol{X})$ to leave the region where its value is less than 0.98 (indicating a 2% muscle contraction). The results for all three subjects at the four critical time frames of /ə/, /s/, /u/, and /k/ are shown in Figure 4. At each time frame, the mask of the whole tongue is rendered using a red volume and the thresholded compressed region with a greater than 2% contraction is rendered using a green volume inside the tongue mask.

Quantitatively, we computed the percentage of compressing muscles for all subjects (the percentage of green regions to the red volume). We plotted both the absolute volumes of the active regions and its percentage to the whole tongue's volume over time in Figure 5. Control 1 is shown in red, control 2 is shown in blue, and the patient is shown in green. Especially, at the four critical frames /ə/, /s/, /u/, and /k/, control 1 reported percentages of 37%, 44%, 35%, and 33%, control 2 reported percentages of 22%, 29%, 34%, and 36%, and the patient reported 26%, 28%, 32%, and 34%.

4. DISCUSSION

From the subject-specific atlas results in Figure 2, it can be seen that the motion fields of all three subjects follow the same pattern. In the pre-speech neutral position /ə/, the whole tongue shows less amount of activity or some motion that points back and down. This is the tongue naturally retracting and getting ready for the upcoming deformations. At /s/, the anterior genioglossus compresses to send the tongue tip forward. Then the tongue moves to an intermediate position with /u/, and ends by pronouncing /k/ where posterior and inferior genioglossus compresses to push the tongue upward. Even for the patient, although his tongue shape is changed due to atrophy and the muscles have a limited extent of deforming ability, the remaining part of the tongue muscles still functions to make a relatively small part of the tongue tip go forward for /s/ and then go upward for /k/.

Qualitatively, the region of compression results shown in Figure 4 is difficult to visually interpret. However, we can observe the general trend of the region of compressing muscles gradually shifting from anterior tongue to posterior tongue during the utterance “a souk”. Especially, comparing the time frames /s/ and /k/, the former has many active regions near the tip of the tongue for all three subjects, while the latter has less amount of activities in these regions. This could be related to the compression of anterior genioglossus to create the central groove for /s/. Meanwhile, the time frame /k/ has many active regions around the posterior tongue comparing to /s/. This could be attributed to posterior genioglossus compressing to shorten the length of the tongue and squeeze it upward.

Notice that in this experiment, the patient does not show much difference from the two controls other than in the tongue shape. From Figure 5, the patient’s percentage of compressed tissues in the tongue is similar to the two controls, especially to that of control 2. The tractography results in Figures 1 and 3 showed a major decrease in the amount of vertical (inferior-superior) fibers in the tongue for the patient. We also note that during the experiment session, the ALS patient still had the ability to produce intelligible speech to a certain extent, although he was not eligible to participate in a dynamic motion scan of the tongue due to speech fatigue and poor repeatability. This result shows that atrophy in some vertical tongue muscle fibers does not severely affect the general location and percentage of compressing tissues during the pronunciation of “a souk”.

Another reason that the patient result looks similar to the controls could be because all three atlases come from the same group of normal control subjects. Since patient’s motion is largely unpredictable, how to simulate a patient’s true motion or even to build an atlas space using a certain group of patients is very challenging. Another direction to aim for improvement is to acquire dynamic motion data directly from ALS patients using our imaging techniques in conjunction with motion correction strategies such as post-processing or wireless MR active markers [18]. Overall, our study proposed a way to simulate a subject’s motion field using a 4D motion atlas without directly acquiring motion data from patients. Although this study is still in a preliminary stage and only three DTI subjects were involved, it proves that atlases of the tongue could be used in a statistical way to analyze motion in subject-specific spaces and to compensate for missing information. In addition, our approach sets a potential direction for providing more insight into the detrimental effects of ALS on speech.

5. CONCLUSION

In this work, we proposed a method to combine information obtained from tagged and diffusion MRI to construct a dynamic strain map in the line of action of internal tongue muscles during speech. With the aid of a 4D motion atlas, the strain map provides a tool to assess the functionality characteristics of normal tongue motion and degenerated ALS motion, and has the potential provide more insight into the detrimental effects of ALS on speech.

Acknowledgments

This work was supported in part by NIH R00DC012575, R01DC014717, R01CA133015, and MGH ECOR ISF funding.

References

1. Zarei S, Carr K, Reiley L, Diaz K, Guerra O, Altamirano PF, Pagani W, Lodin D, Orozco G, Chinea A. A comprehensive review of amyotrophic lateral sclerosis. Surgical neurology international. 2015; 6
2. Kiernan MC, Vucic S, Cheah BC, Turner MR, Eisen A, Hardiman O, Burrell JR, Zoing MC. Amyotrophic lateral sclerosis. The Lancet. 2011; 377(9769):942–955.
3. Parthasarathy V, Prince JL, Stone M, Murano EZ, NessAiver M. Measuring tongue motion from tagged cine-MRI using harmonic phase (HARP) processing. The Journal of the Acoustical Society of America. 2007; 121(1):491–504. [PubMed: 17297803]
4. Xing F, Woo J, Lee J, Murano EZ, Stone M, Prince JL. Analysis of 3-D tongue motion from tagged and cine magnetic resonance images. Journal of Speech, Language, and Hearing Research. 2016; 59(3):468–479.
5. Osman NF, McVeigh ER, Prince JL. Imaging heart motion using harmonic phase MRI. Medical Imaging, IEEE Transactions on. 2000; 19(3):186–202.
6. Liu X, Abd-Elmoniem KZ, Stone M, Murano EZ, Zhuo J, Gullapalli RP, Prince JL. Incompressible deformation estimation algorithm (IDEA) from tagged MR images. IEEE transactions on medical imaging. 2012; 31(2):326–340. [PubMed: 21937342]
7. Xing F, Woo J, Gomez AD, Pham DL, Bayly PV, Stone M, Prince JL. Phase vector incompressible registration algorithm (PVIRA) for motion estimation from tagged magnetic resonance images. IEEE Transactions on Medical Imaging. 2017; 36(10):2116–2128. [PubMed: 28692967]
8. Hagmann P, Jonasson L, Maeder P, Thiran JP, Wedeen VJ, Meuli R. Understanding diffusion MR imaging techniques: from scalar diffusion-weighted imaging to diffusion tensor imaging and beyond. Radiographics. 2006; 26(suppl_1):S205–S223. [PubMed: 17050517]
9. Wakana S, Caprihan A, Panzenboeck MM, Fallon JH, Perry M, Gollub RL, Blitz A. Reproducibility of quantitative tractography methods applied to cerebral white matter. Neuroimage. 2007; 36(3): 630–644. [PubMed: 17481925]
10. Basser PJ, Pajevic S, Pierpaoli C, Duda J, Aldroubi A. In vivo fiber tractography using DT-MRI data. Magnetic resonance in medicine. 2000; 44(4):625–632. [PubMed: 11025519]
11. Gaige TA, Benner T, Wang R, Wedeen VJ, Gilbert RJ. Three dimensional myoarchitecture of the human tongue determined in vivo by diffusion tensor imaging with tractography. Journal of Magnetic Resonance Imaging. 2007; 26(3):654–661. [PubMed: 17685446]
12. Shinagawa H, Murano EZ, Zhuo J, Landman B, Gullapalli RP, Prince JL, Stone M. Tongue muscle fiber tracking during rest and tongue protrusion with oral appliances: A preliminary study with diffusion tensor imaging. Acoustical science and technology. 2008; 29(4):291–294.
13. Xing F, Ye C, Woo J, Stone M, Prince J. Relating speech production to tongue muscle compressions using tagged and high-resolution magnetic resonance imaging. Proceedings-Society of Photo-Optical Instrumentation Engineers. 2015; 9413:94131L–94131L.

14. Woo J, Xing F, Lee J, Stone M, Prince JL. A spatio-temporal atlas and statistical model of the tongue during speech from cine-MRI. Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization. 2016:1–12. [PubMed: 29623248]
15. Woo J, Xing F, Stone M, Green J, Reese TG, Brady TJ, Fakhri GE. Speech Map: A Statistical Multimodal Atlas of 4D Tongue Motion During Speech from Tagged and Cine MR Images. arXiv preprint arXiv:1701.06708. 2017
16. Xing F, Prince JL, Stone M, Wedeen V, El Fakhri G, Woo J. A four-dimensional motion field atlas of the tongue from tagged and cine magnetic resonance imaging. Proceedings-Society of Photo-Optical Instrumentation Engineers. 2017:101331H–101331H.
17. Ehrhardt J, Werner R, Schmidt-Richberg A, Handels H. Statistical modeling of 4D respiratory lung motion using diffeomorphic image registration. IEEE transactions on medical imaging. 2011; 30(2):251–265. [PubMed: 20876013]
18. Huang C, Ackerman JL, Petibon Y, Normandin MD, Brady TJ, El Fakhri G, Ouyang J. Motion compensation for brain PET imaging using wireless MR active markers in simultaneous PET–MR: Phantom and non-human primate studies. NeuroImage. 2014; 91:129–137. [PubMed: 24418501]

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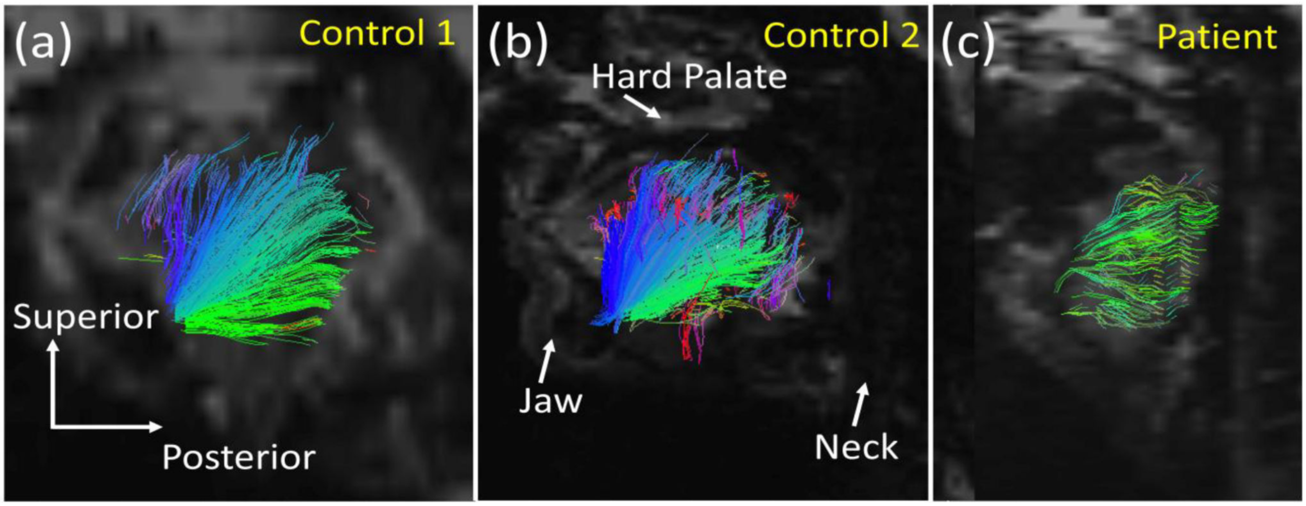

Figure 1.
Tractography of the internal tongue muscle fibers around the genioglossus region of two normal controls and an ALS patient.

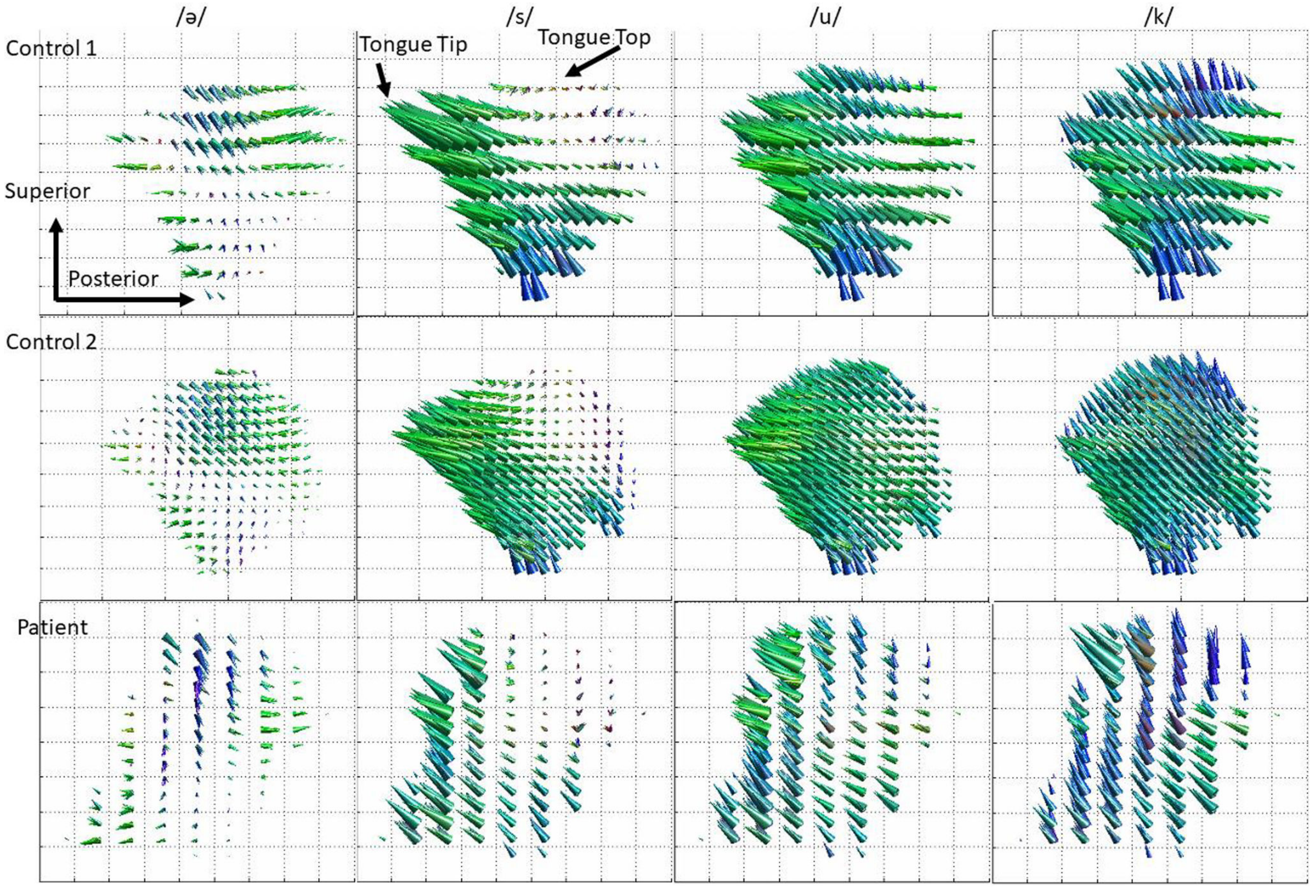

Figure 2.

4D motion atlases constructed from fourteen tMRI sequences in the b0 spaces of two normal control subjects and an ALS patient pronouncing the utterance "a souk". Four critical time frames from 26 total frames are shown, representing a neutral position, a forward motion, an intermediate motion between /s/ and /k/, and an upward motion. We use color-coded cones to represent motion directions, where anterior-posterior is coded green, inferior-superior is coded blue, and left-right is coded red.

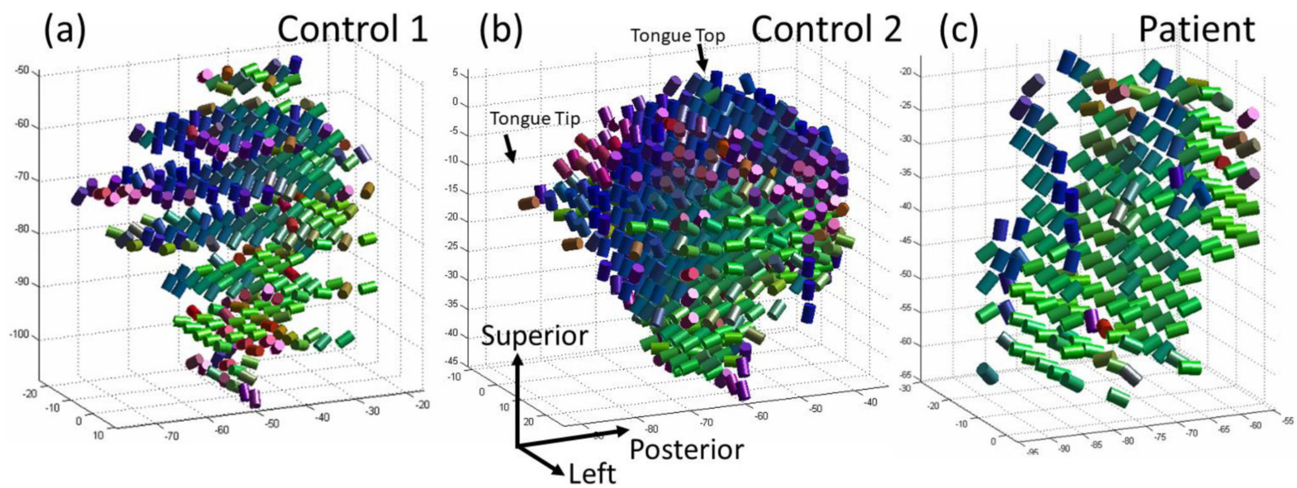

Figure 3.

Major internal tongue muscle fiber directions from DTI tractography of two normal control subjects and an ALS patient. The color-coding scheme is the same as above, where anterior-posterior is coded green, inferior-superior is coded blue, and left-right is coded red.

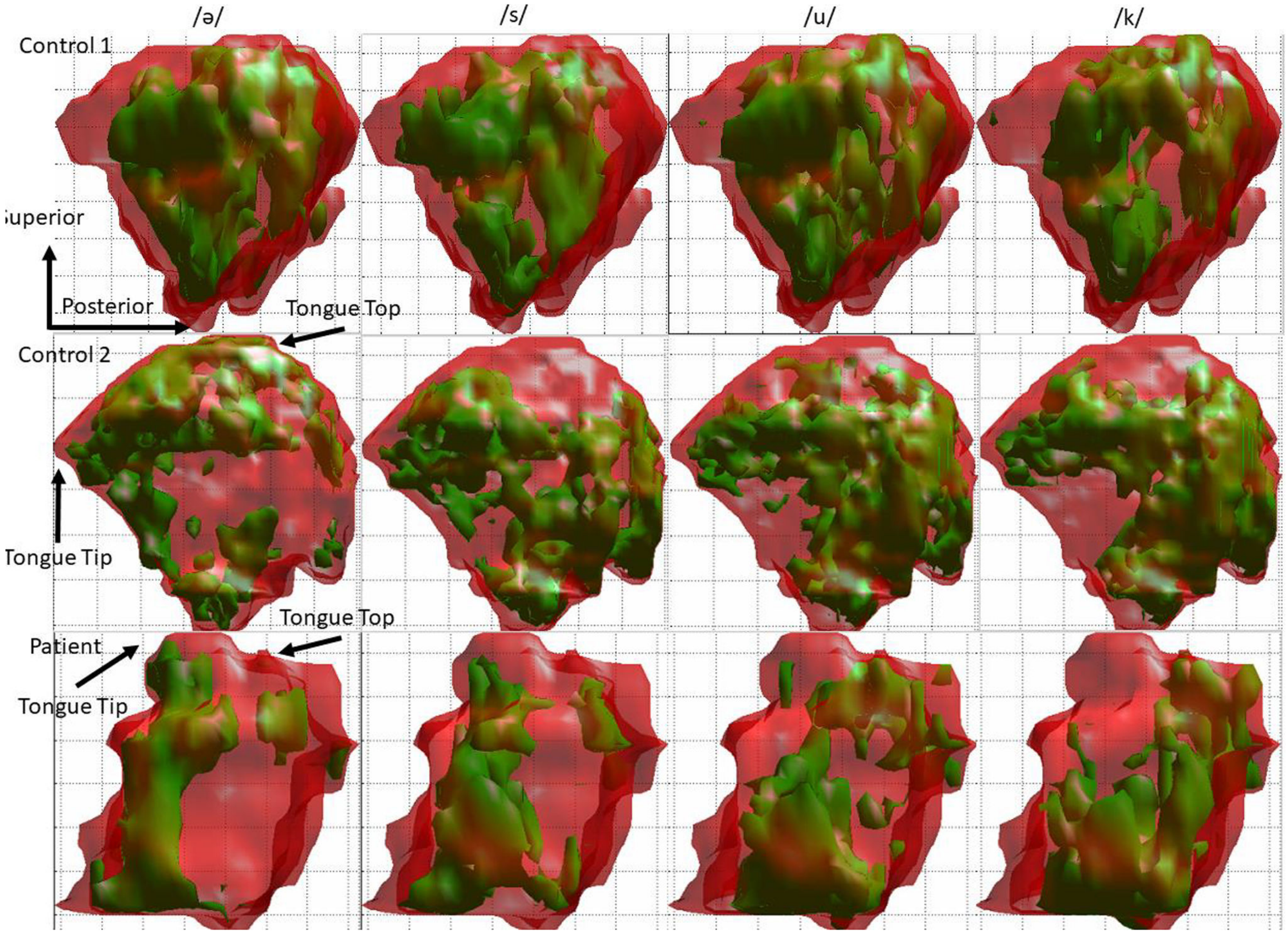

Figure 4.
Contracting regions (green) with more than 2% of original muscle length in the whole tongue (red) when pronouncing “a souk” for two normal control subjects and an ALS patient.

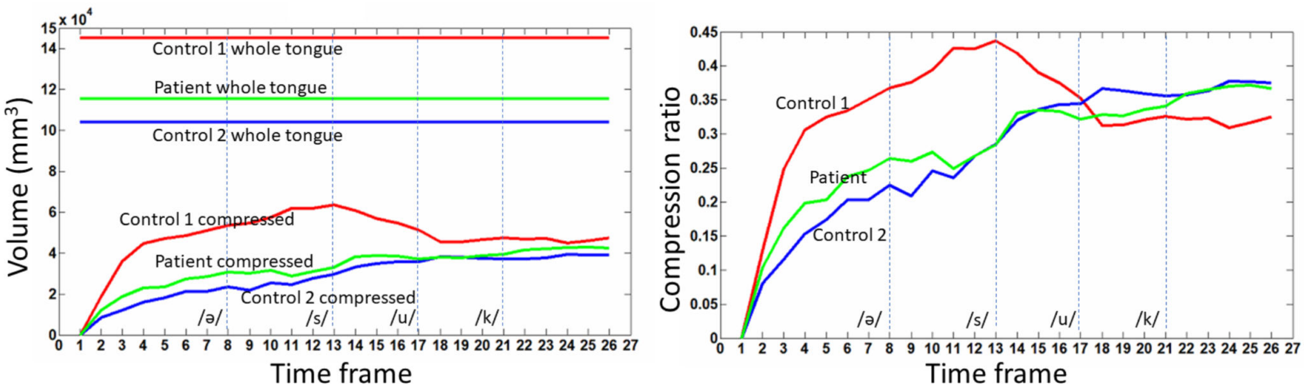

Figure 5.

Volume change of the compressed regions in the tongue through time. The left figure shows the absolute volume in mm^3 of both the compressed regions and the whole tongue. The right figure shows the ratio of the compressed regions in the whole tongue over time.