A muscle synergy approach in evaluation of the gait complexity following surgical alignment

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Abstract—Adult Degenerative Scoliosis (ADS) is a common musculoskeletal problem that commonly affects the elderly. ADS patients often suffer from low back pain and consequently have reduced mobility. Surgical alignment is one of the possible treatments in ADS patients. Due to the highly variant nature of the ADS, tracking and comparing the improvements following surgery can be challenging. Muscle synergy theory suggests that the central nervous system may use a few groups of coactive muscles (i.e., synergies) to achieve a motor task. In this study, we propose to use muscle synergy approach to determine the recovery from the ADS following surgery. More specifically, two metrics are proposed: i) the number of the required muscle synergies for a motor task and ii) Entropy. Entropy is a measure of uncertainty in the data and has been shown to be sensitive to detect functional enhancement. We hypothesize that the number of muscle synergies required for walking increases following surgery. We also hypothesize that entropy associated with the muscle synergies decreases following surgery. The results showed that the patients required a significantly higher number of walking muscle synergies following a surgery. Also, the entropy value decreased significantly in ADS patients following surgical procedures, showing a more deterministic control. A muscle synergy approach in tracking the improvements in motor skills could be advantageous as it considers all of the involved muscles together, bypassing the potential subject-dependent differences.

Index Terms—Scoliosis, ADS, gait, muscle synergies, entropy.

I. INTRODUCTION

ADULT degenerative scoliosis (ADS) is generally defined as an abnormal 3D (mainly lateral) curvature of the spine caused by asymmetric degeneration of discs [1], [2]. ADS is a common musculoskeletal problem in the elderly, affecting up to 68% of their population with an average age of 70 years old [2]–[5]. ADS patients often suffer from back pain, shooting leg pain, and unnatural spine curvature that affects their gait; hence, surgical intervention is one of the potential treatment strategies to reestablish the disk spacing that causes the deformity [2], [6]. Although surgical treatment has resulted in a significant improvement in measures such as back curvature, low back pain, and quality of life, given the invasive nature of the operation and exposure of the spine, secondary complications such as infection, neurological deficit, and risk of death are possible [1], [6]. Most importantly,

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due to the significant dissection and trauma, patients have to be hospitalized and immobilized for an extensive amount of time until their recovery [6]–[8]. Not only would the slow recoveries along with the lengthy lack of mobility put patients at higher risk of secondary conditions, but also it would make it challenging to evaluate their improvements following surgery.

Improvement in ADS patients could be measured with numerous variables such as pain levels measured by visual analog scale (VAS), the severity of the deformity (commonly quantified via measuring the angle of curvature using Cobb's method measured by radiography [9]), and gait symmetry index. These variables try to provide measures that indicate an enhancement in the and quality of daily life, and how advanced and complex the patients could perform specific motor tasks, such as gait. Nonetheless, due to the high prevalence and subject-specific nature of ADS, patients can vary in numerous aspects such as the affected side (i.e., left or right), Cobb angle, number and location of the affected disks (e.g., T7-L3), and unique 3D curvature of the spine. This high variation can further hinder the tracking of the gait complexity (i.e., a measure of gait quality) following surgery, since subjects may show higher/lower activation in different muscle groups on different sides to different degrees. Hence, a novel measure is required that considers all muscles and provides a generalized complexity index robust to the aforementioned subject-specific variations.

The concept of entropy might serve this purpose. Entropy has existed for a considerable amount of time in fields like thermodynamics, statistics, and information theory. Entropy is a quantity presenting randomness, disorder, and lack of information. Although entropy has shown promise in explaining the behavior of systems in different areas, it has been seldom used in the field of biomechanics [10]–[12]. According to [11], [12], a decrease in entropy is associated with an enhancement in postural balance, since less entropy expresses less chaotic and more deterministic control to move the center of mass only in directions ensuring a more secure balance. Reduced entropy in postural balance may be related to increased neuromuscular sensitivity or sensation [11]–[14]. Similarly, one may expect to observe a decrease in gait's entropy values upon surgical interventions indicating potential improvements. As a result, the entropy of the muscles would be robust to the variations observed in ADS patients as it considers all muscles at the same time.

As importantly, the concept of muscle synergies could be another candidate for indicating complexity. Studies have shown that the CNS might use a limited set of control inputs to activate a group of muscles rather than controlling them

individually. This set of lower-dimensional control blocks, often referred to as muscle synergies, has been used by different research groups to explain and account for the variations observed in a variety of motor tasks such as walking, swimming, and kicking. Researchers often fix the number of used muscle synergies to account for 95% of the variation observed in the collected electromyographic (EMG) signals from the target muscles.

The number of muscle synergies is of importance as studies have indicated an association between a greater number of required muscle synergies and higher quality and complexity of the performed motor task [15]–[17]. In other words, participants who require a higher number of synergies for the same task often present a higher quality of the motor task. For example, studies have shown that post-stroke patients who had a superior gait quality and residual function utilized a greater number of walking muscle synergies [15], indicating their CNS ability in generating independent control signals. Also, previous studies have interpreted an increase in the number of muscle synergies as a measure to indicate post-surgery improvements [16]. Since muscle synergies have shown more promise and robustness in explanation of the motor tasks [18]–[22], we suspect that using the number of muscle synergies can facilitate the tracking of gait improvements following surgical alignments despite the subject-specific conditions discussed above.

The objective of this study is to examine the number of muscle synergies and their associated entropy as a measure of gait improvement/complexity following surgical interventions in ADS patients. Both the number and the entropy of synergies would be compared both before and three months after surgery to detect significant improvements. We hypothesize that the number of utilized walking muscle synergies would show a significant increase indicating a more complex and richer gait control, while their associated entropy would decrease, showing a more deterministic and goal-directed control towards the gait.

II. METHODS

A. Participants

Clinical gait analysis was performed on thirteen ADS patients (Average age: 61.77 (SD=11.19), Sex: 8 female/5 male), one week prior, and three months post-surgery. Participants were recruited from the ClinicalTrials.gov (registration no.: NCT02761265) and gave written consent before participation in this IRB-approved study (Western Institutional Review Board, #20151780). To maintain a moderate severity of ADS, participants were excluded in the case of a Cobb angle larger than 50 degrees (as a controlling factor for their ADS severity). Participants had at least four fused levels in thoracic, lumbar, and thoracolumbar parts.

B. Experimental Protocol

Five walking trials were performed at the self-selected speed of the patients for data collection. Patients were asked to walk normally in a walkway with three force plates embedded. The starting position was adjusted to secure one heel-strike per force plate (AMTI Corp, Watertown, MA). Force data were sampled at 2000 Hz. Surface electromyographcic (EMG) data (Trigno, Delsys, Inc, Natick, MA) were wirelessly collected at 2000 Hz from sixteen trunk and lower extremity muscles: External Oblique, Gluteus Maximus, Multifidus (at the level of L5), Erector Spinae (at the level of L1), Rectus Femoris, Semitendinosus, Tibialis Anterior, Medial Gastrocnemius, bilaterally.

C. Data Analysis

1) Data normalization: The EMG data were high-pass filtered at 20 Hz, low-passed at 450 Hz, demeaned, rectified, and low-passed at 35 Hz with zero-lag Butterworth filter via MATLAB (v2017b, The MathWorks, Natick, MA). The data was then normalized to the maximum activity observed among all trials of each participant.

2) Synergy extraction and VAF: Then the processed EMG was used in a non-negative matrix factorizer to extract walking muscle synergies and their activation coefficients using the methods described in [19], [21]. The number of synergies were varied, starting from one to sixteen (maximum possible due to the number of recoded muscles). Then, "the required number of synergies" was found as the minimum number of synergies that could reconstruct EMG signals with a *Variance Accounted For* (VAF) higher than 95%, defined as:

$$\text{VAF} = 1 - \frac{\text{EMG}_{\text{processed}} - \text{EMG}_{\text{reconstructed}}}{\text{EMG}_{\text{processed}}} \tag{1}$$

This procedure was done for every participant, both pre- and post-surgery.

3) Stochastic vector and Entropy: Upon fixing the number of muscles, an entropy for each synergy was calculated. The concept of an entropy is often used on probability functions in which the summation of all possible events is equal to one. Computing the entropy of biomechanical data is not unique and may require redefinition and discretization of states [12]. Luckily, entropy of each synergy can be computed in a simple way. First, considering each synergy as an activation vector of all muscles, the summation of all muscular activation in the synergy vector (e.g., bars in Fig. 2a) was rescaled to one, to enforce each synergy (e.g., each bar in Fig. 2b) to resemble a probability density function. The rescaled synergy vector is called a *stochastic vector*. Then, the entropy of each muscle synergy (i.e., stochastic vector) of each participant was defined as:

$$H(W_i) = -\sum_{j=1}^{n} P(j) \log_2 P(j) \tag{2}$$

where H is the entropy value, W_i is the ith muscle synergy, n is the total number of muscles, and $P(j)$ is the rescaled muscle synergy value of the jth muscle within the ith muscle synergy vector (i.e., stochastic vector) (Fig. 2b) and is entitled to be a probability.
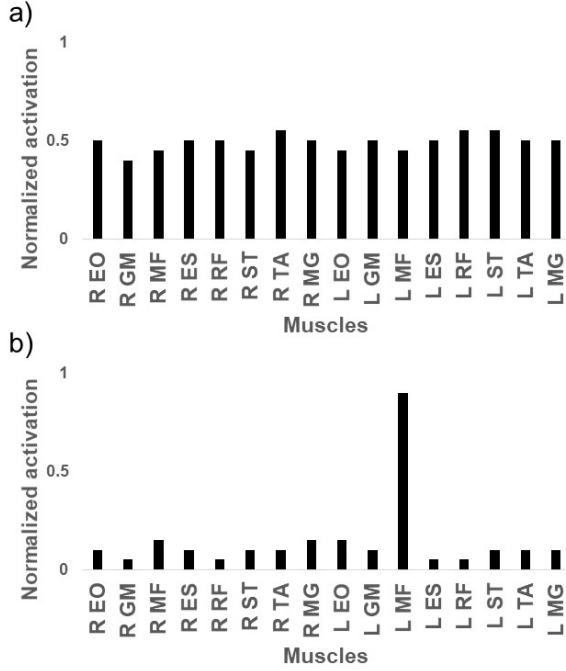
Fig. 1. Two generic muscle synergies with high entropy (a) and low entropy (b) values. (a) has more randomness and disorder whereas (b) has more determinism and goal-directedness. Note that synergies in both (a) and (b) need to be rescaled to become stochastic vectors so that Eq. 2 can be directly used.

TABLE I
REQUIRED NUMBER OF WALKING SYNERGIES PRE- AND POST-SURGERY, AND T-TEST RESULTS.

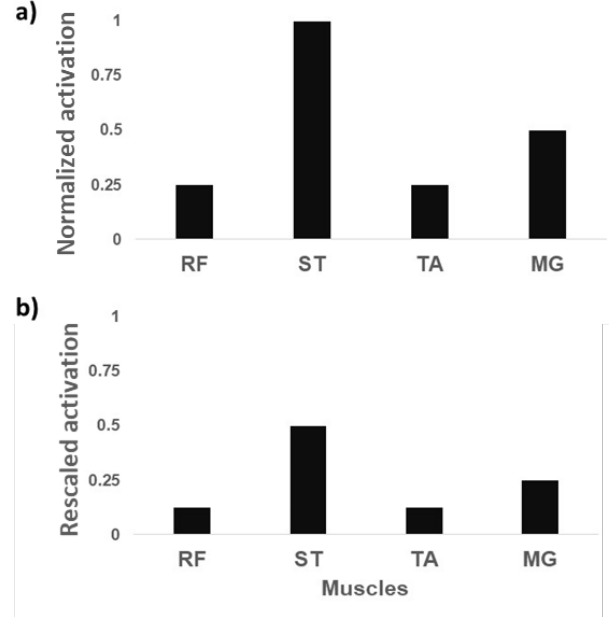|	Pre-surgery	Pre-surgery	p-value
Number of synergies (Mean $\pm$ SD)	4.46 ± 1.33	5.07 ± 1.44	0.04

Fig. 2. Ordinary normalized (a) and rescaled (b) muscle synergies. Note that sum of all bars in (b) is one (i.e., stochastic vector). Then, each bar in (b) can be treated as probability $P(j)$ where $j = \{$RF,ST,TA,MG$\}$ and Eq. 2 can be directly used.

D. Statistical Analysis

The minimum required number of synergies to reconstruct EMG signals with a VAF higher than 95% pre- and post-surgery were compared with a paired t-test ($\alpha = 0.05$) using SPSS (v21, IBM, Chicago, IL). Similarly, the pre- and post-surgery entropy were compared using a paired t-test via SPSS (v21, IBM, Chicago, IL) to identify the potential differences at a significance of $\alpha = 0.05$ [21], [23]. There is one technical issue when comparing the entropy of the extracted muscle synergies pre- and post-surgery.

In order to perform a one-to-one comparison of the extracted muscle synergies, the same number of muscle synergies had to be extracted for each participant. This number was set to ensure the encompassment of the most synergies of the majority of the participants. To do so, using the mean and standard deviation value for the number of synergies in different individuals, a confidence interval was built, and the number was selected to be the upper bound of a 95% confidence interval, using the following equation:

$$\mu \leq \bar{x} + \sigma \times z \quad (3)$$

where μ is the upper bound for the true mean, $\bar{x}$ is the sample mean value, σ is the standard deviation, and z is the critical value for the normal distribution to ensure a 95% encompassment with a significance of 0.05. Then, the bound for the true mean was rounded to the closest whole number.

III. RESULTS

First, muscle synergies pre- and post-surgery were computed. The number of the required synergies (i.e., Eq. 1) for each participant was compared before and after surgery. The t-test revealed a significant increase in the number of required muscle synergies for walking in ADS patients following a surgical procedure (Table I).

Second, to run the one-to-one comparison of the synergies, an equal number of synergies needed to be extracted for all participants. The z-value was extracted to be 1.64 from statistics references. Then, according to the values reported in Table I and using Eq. 3, it was found that seven muscle synergies would serve as an upper bound for 95% of participants both before and after surgery. Consequently, in our secondary analysis, irrespective of Eq. 1 and the number of the required synergies, seven muscle synergies were extracted for every individual (Fig. 2). The paired t-test also showed a highly significant reduction in the measured entropy following surgical interventions presented in Table II.

A clinical comparison following surgery showed that all participants had improved significantly in different variables such as Cobb angle, pain level, functional balance, cadence, step length, single support time, and gait deviation index, all with p-values < 0.05 [24].

TABLE II
REQUIRED NUMBER OF WALKING SYNERGIES PRE- AND POST-SURGERY, AND T-TEST RESULTS.

Muscle synergy	W1	W2	W3	W4	W5	W6	W7
Pre-surgery entropy	3.26 ± 0.24	3.41 ± 0.17	3.22 ± 0.25	3.31 ± 0.19	3.30 ± 0.18	3.36 ± 0.21	3.30 ± 0.22
Post-surgery entropy	2.99 ± 0.30	3.22 ± 0.17	2.87 ± 0.28	3.09 ± 0.23	3.14 ± 0.22	3.17 ± 0.22	3.02 ± 0.25
p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0013	0.0003	< 0.0001

IV. DISCUSSION

The results from [24] indicated that ADS patients have been clinically improved upon surgery. Prolonged single stance phase of the gait along with longer step lengths indicate the ability of the participants to maintain their balance on one limb for longer periods. These results confirm our hypothesis about number of required muscle synergies. ADS patients required a higher number of synergies to present their walking following a surgical alignment. As discussed before, a higher number of synergies is associated with richer control signals that require more vectors (i.e., synergies) to be rebuilt [15], [16]. Hence, we suggest that the surgery has improved the gait quality for ADS patients at their three-months follow up. We also suspect that the observed changes are probably due to a reduction in pain levels of participants [24]. Although the relation between motor control and pain is an ongoing research topic, pain adaption theories claim that pain affects motor control [25]. Researchers believe that low back pain (which is highly prevalent in ADS patients) has the potential to change the co-activation patterns in a way to restrict spine movements as a measure to minimize the pain [26]–[29].

Furthermore, the same researchers claimed that pain does not necessarily cause inhabitation or excitation of the muscles; however, it may bring a redistribution of the activity within or between synergist muscles [27]. Hence, observation of changes in muscle synergies following surgery should be inevitable. Our results support this hypothesis by presenting a redistribution in muscle activities throughout muscle synergies following surgical interventions in ADS patients (Fig. 3). Moreover, studies claim that in order to protect the body from pain, the central nervous system may decrease the activation levels in agonist muscle groups and increase the activation in the antagonist group as a measure to increase the joint stiffness in order to restrict the range of motion in joints [27], [28], [30]. Excessive activation of the antagonist muscles in synergies would increase the entropy by definition, as it requires activation of a greater number of muscles that is equivalent to less deterministic control. This theory stays highly consistent with our results that show a significant decrease in the entropy of walking synergies of ADS patients following surgery, which can be due to a reduction in the unnecessary co-activations enforced to reduce the pain. Our future studies would try to correlate a pain level questionnaire with the observed entropies to further verify our hypothesis.

The decrease in entropy also substantiates our initial hypothesis. We speculated that a lower entropy would be associated with a less random and more deterministic control of the muscles by the CNS that ultimately results in an improved gait.

In other words, the CNS may more deliberately choose muscle activations in a way to secure a more stable gait. A similar concept had been presented before on balance studies [10], [11]. However, our study is the first to examine the concept of entropy in human gait. Due to the association between the clinical gait parameters and the decrease in entropy, we claim that studying the entropy can potentially be used as a yardstick to track the improvements in gait, specifically in the presence of high subjective variations.

V. CONCLUSION

This study examined the potential of the number of muscle synergies and their associated entropy in tracking the gait improvements of ADS patients following surgery. The patients who had already shown clinical gait improvements showed an increase in the number of required walking muscle synergies. Requiring a higher number of synergies could be an indicator of requiring more control signals to control the gait, which is associated with more advanced control. Also, the entropy associated with those synergies dropped significantly. A lower entropy may represent a more deterministic control of the limbs and maybe a beneficial tool in tracking the rehabilitation of patients. Future studies would try to examine the association between the observed clinical improvements and the evolution of muscle synergies. Also, we are interested in performing the same analysis on the participant at their one-year follow-up to observe the course of changes in the entropy and number of muscle synergies.

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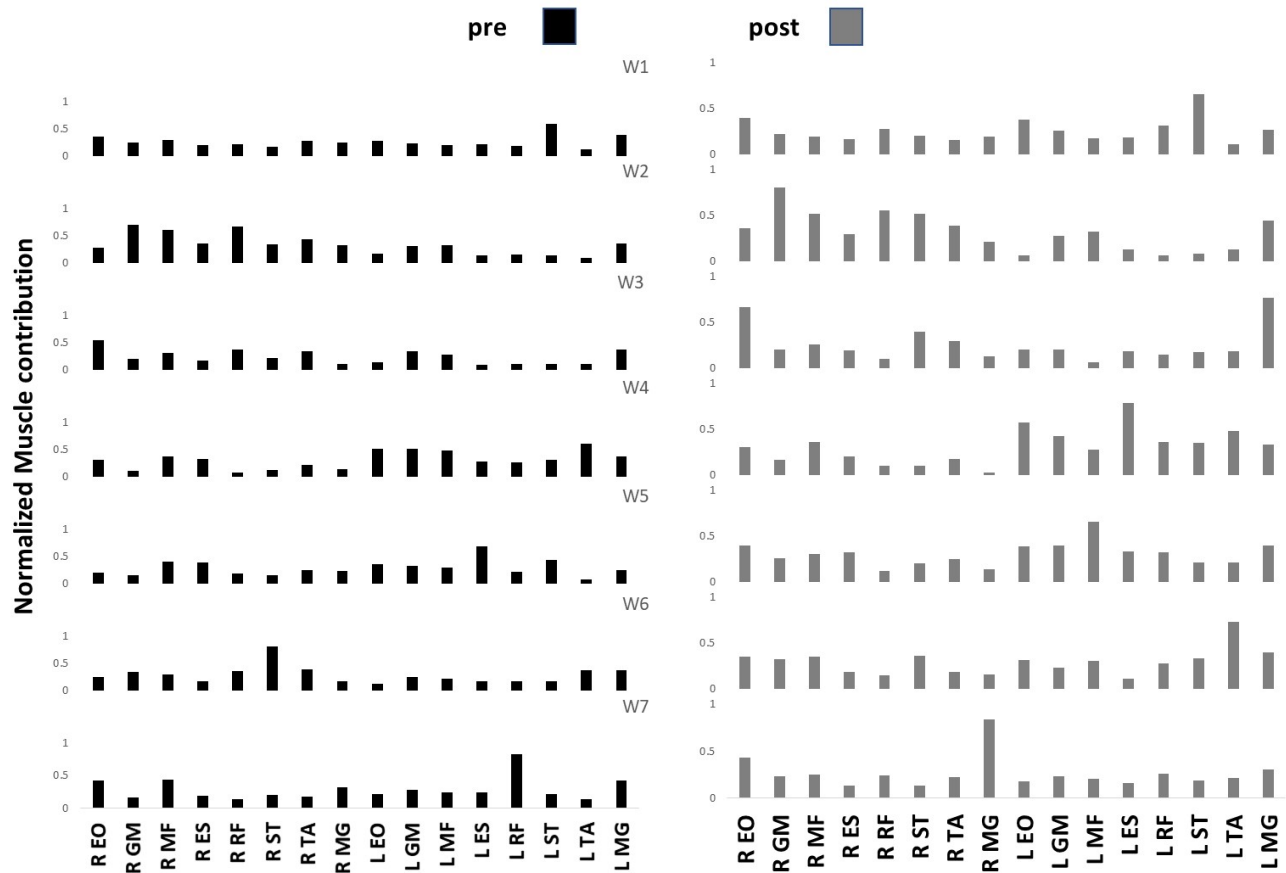
Fig. 3. Pre- and Post-surgery walking muscle synergies.

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