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

Mohammad Moein Nazifi
Harvard Medical School
Isador Lieberman
Texas Back Institute
Ram Haddas
Texas Back Institute
Pilwon Hur (pilwonhur@gist.ac.kr)
Gwangju Institute of Science and Technology

Research Article

Keywords: Scoliosis, ADS, gait complexity, muscle synergies, entropy

Posted Date: April 20th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1559062/v1

RESEARCH

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

Mohammad Moein Nazifi[1], Isador Lieberman[2], Ram Haddas[3] and Pilwon Hur[4*]

[*]Correspondence: pilwonhur@gist.ac.kr
[4]School of Mechanical Engineering, Gwangju Institute of Science and Technology, Cheomdangwagi-ro, 61005 Gwangju, Korea
Full list of author information is available at the end of the article

Abstract

Background: 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.

Methods: 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) an entropy-inspired measure (EnIM). Entropy is a measure of uncertainty in the data and has been shown to be sensitive to detect functional mobility enhancement. We hypothesize that the number of muscle synergies required for walking increases following surgery. We also hypothesize that EnIM associated with the muscle synergies decreases following surgery.

Results: The results showed that the patients required a significantly higher number of walking muscle synergies following a surgery. Also, EnIM decreased significantly in ADS patients following surgical procedures, showing a more deterministic control.

Conclusions: 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.

Trial registration: Western Institutional Review Board, #20151780. Participants were recruited from the ClinicalTrials.gov (registration no.: NCT02761265)

Keywords: Scoliosis; ADS; gait complexity; muscle synergies; entropy

Background

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 [3, 2, 4, 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, due to the significant dissection and trauma, patients have to be hospitalized and immobilized for an extensive amount of time until their recovery [7, 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 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 [10] can further hinder the tracking of gait recovery 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 gait recovery index robust to the aforementioned subject-specific variations.

The concept of muscle synergies can be used to indicate complexity which is known to measure the quality of movement [11, 12, 13] and gait [14, 15]. 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 [16, 17, 18, 19].

The number of muscle synergies accounting for 95% of movement variation is of importance as studies have indicated the association between a greater number of required muscle synergies and higher quality and complexity of the performed motor task [13, 11, 12]. 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 [13], indicating the ability of the CNS in generating independent and sophisticated control signals. Also, previous studies have interpreted an increase in the number of muscle synergies as a measure to indicate post-surgery improvements [11]. Since muscle synergies have shown a promise and robustness in explanation of the motor tasks [20, 17, 18, 19, 16], 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.

In addition, the concept of entropy might serve this purpose. Entropy is a quantity presenting randomness, disorder, and lack of information. Entropy has been used in fields like thermodynamics, statistics, and information theory. Some researchers examined its use in motor control and biomechanics. According to [21, 22], 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 indicated enhanced sensorimotor responses and thus enhanced balance [22, 23, 24, 21]. CNS which cannot efficiently decrease the entropy may indicate inefficient neural controls of the biological systems [25]. Although entropy has shown promise in explaining the behavior of human walking and balance [25, 21, 22, 26], to our best knowledge, it has never been used with muscle synergy of human movements. Based on these observations, one may expect to define an entropy-inspired measure that quantifies the uncertainty of muscle synergies upon surgical interventions, indicating potential improvements. In this way, the entropy-inspired measure can provide a robust metric even in the presence of the high variations observed in ADS patients.

The objective of this study is to examine the number of muscle synergies and their associated entropy-inspired measure (EnIM) as metrics of gait recovery following surgical interventions in ADS patients. Both the number and the entropy-inspired measure 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-inspired measure would decrease, showing a more deterministic and goal-directed control towards the gait.

Methods

Participants

Thirteen ADS patients (Average age: 61.77 (SD=11.19), Sex: 8 female/5 male) 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.

Experimental Protocol

Five walking trials were performed at the self-selected speed of the patients for data collection one week prior, and three months post-surgery. 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.

Data Analysis

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 were then normalized to the maximum activity for each muscle observed among all trials of each participant.

Synergy extraction and VAF

The processed EMG data were decomposed with a non-negative matrix factorizer to extract walking muscle synergies and their activation coefficients using the methods described in [17, 19]. The number of synergies were varied, starting from one to sixteen (maximum possible due to the number of recorded 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% [16, 17, 18, 19], defined as:

$$\text{VAF} = 1 - \frac{\|\text{EMG}_{\text{processed}} - \text{EMG}_{\text{reconstructed}}\|_F^2}{\|\text{EMG}_{\text{processed}}\|_F^2} \tag{1}$$

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

Entropy-inspired Measure

Upon fixing the number of muscles, an Entropy-inspired Measure (EnIM) for each synergy was calculated. The concept of an entropy is often used on probability distributions in which the summation of the probability 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 [22]. Luckily, an entropy-like measure of each synergy can be computed in a relatively 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) is rescaled to one to enforce each synergy (e.g., each bar in Fig. 2b) to resemble a probability density function. Then, the entropy-like measure of each rescaled muscle synergy of each participant is computed 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 (Fig. 2b). Please note that we treated the rescaled muscle synergy vectors as probability density functions to compute the entropy-like values via Eq. 2. In this study, we denote the entropy-like value by the Entropy-inspired Measure (EnIM).

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 EnIM were compared using a paired t-test via SPSS (v21, IBM, Chicago, IL) to identify the potential differences at a significance of $\alpha = 0.05$ [19, 27].

There is one technical issue when comparing the EnIM 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:

$$\mu \leq \bar{x} + \sigma \times z \tag{3}$$

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.

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 the required muscle synergies for walking in ADS patients following a surgical procedure (Table 1).

Second, to run the one-to-one comparison of the synergies, an equal number of synergies before and after the surgery was extracted for all participants. According to the values reported in Table 1 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(i.e., z-value=1.64). 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 2.

A clinical comparison following surgery showed that all participants had improved significantly in different variables such as Cobb angle, pain level, functional balance, walking speed, stride length, and confidence during walking, all with p-values < 0.05 [28].

Discussion

The results from [28] indicated that ADS patients' gait has been clinically improved upon surgery. Prolonged single stance phase of the gait along with longer stride lengths indicates 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 may have 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 [13, 11]. 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 improvements are probably due to a reduction in pain levels of participants in part [28]. Although the relation between motor control and pain is an ongoing research topic, pain adaption theories claim that pain affects motor control [29]. 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 [30, 31, 32, 33].

Furthermore, the researchers claimed that pain does not necessarily cause inhibition or excitation of the muscles; however, it may bring a redistribution of the activity within or between synergist muscles [31]. 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 in some measure to increase the joint stiffness in order to restrict the range of motion in joints [31, 32, 34]. Excessive activation of the antagonist muscles in synergies would increase the EnIM 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 showing a significant decrease in EnIM 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 EnIM to further verify our hypothesis.

The decrease in EnIM also substantiates our initial hypothesis. We speculated that a lower EnIM 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 previously in balance studies [25, 21]. However, our study is the first to examine the concept of entropy in the muscle synergies of human gait. Due to the association between the clinical gait parameters and the decrease in EnIM, we claim that studying the EnIM can potentially be used as a yardstick to track the improvements in gait, specifically in the presence of high subjective variations.

Conclusion

This study examined the potential of the number of muscle synergies and their associated Entropy-inspired Measure (EnIM) 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 sophisticated control. Also, the EnIM associated with those synergies dropped significantly. A lower EnIM 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 number of muscle synergies and EnIM.

Competing interests
The authors declare that they have no competing interests.

Funding
This study was not funded by any external funding sources.

Ethics approval and consent to participate
All patients provided informed consent, and the study protocol was approved by Institutional Review Board (Western Institutional Review Board, #20151780).

Consent for publication
Consent forms and signed releases were completed by parents of the participants who agreed the publication of the research data and findings.

Availability of data and materials
All data collected in the study are available from the corresponding author upon reasonable request.

Author's contributions
PL designed, coordinated and conducted the experiments and wrote significant portion of the manuscript. YL conducted the experiments, analyzed the data and wrote significant portion of the manuscript. NK designed and coordinated the experiments. PH designed, coordinated, and conducted the experiments, analyzed the data and wrote significant portion of the manuscript. All authors read and approved the final manuscript.

Acknowledgements
Donelle Beal, Bob Byrns, Mattea Much, Teagan Vander Stratten, ROCK (Ride On Center for Kids) and TAMU CC (Texas A&M University Courtney Grimshaw Equine Therapeutic Program) staff, Parson's Mounted Cavalry, Hailey Lenis, Molly Anthony and Michael Dillon for logistical and practical assistance. And, Scott Cook, Jen Howicz, and Lori McClure for editing and manuscript assistance.

Author details
[1]Massachusetts Eye and Ear Center and Harvard Medical School, 243 Charles Street, 02114 Boston, MA, USA. [2]Texas Back Institute, 6020 W Parker Rd, 75093 Plano, TX, USA. [3]Texas Back Institute, 6020 W Parker Rd, 75093 Plano, TX, USA. [4]School of Mechanical Engineering, Gwangju Institute of Science and Technology, Cheomdangwagi-ro, 61005 Gwangju, Korea.

References
1. Birknes, J.K., White, A.P., Albert, T.J., Shaffrey, C.I., Harrop, J.S.: Adult degenerative scoliosis: A review. Neurosurgery **63**, 94–103 (2008)
2. Cho, K.-J., Kim, Y.-T., Shin, S.-H., Suk, S.-I.: Surgical treatment of adult degenerative scoliosis. Asian Spine Journal **8**(3), 371–381 (2014)
3. Olivia D Carter, S.G.H.: Prevalence rates for scoliosis in us adults: results from the first national health and nutrition examination survey. International Journal of Epidemiology **16**(4), 537–544 (1987)
4. Schwab, F., Dubey, A., Gamez, L., Fegoun, A.B.E., Hwang, K., Pagala, M., Farcy, J.-P.: Adult scoliosis: Prevalence, sf-36, and nutritional parameters in an elderly volunteer population. Spine **30**(9), 1082–1085 (2005)
5. Silva, F.E., Lenke, L.G.: Adult degenerative scoliosis: Evaluation and management. Neurosurgical Focus **28**(3), 1 (2010)
6. Dakwar, E., Cardona, R.F., Smith, D.A., Uribe, J.S.: Early outcomes and safety of the minimally invasive, lateral retroperitoneal transpsoas approach for adult degenerative scoliosis. Neurosurgical Focus **28**(3), 8 (2010)
7. Benglis, D.M., Elhammady, M.S., Levi, A.D., Vanni, S.: Minimally invasive anterolateral approaches for the treatment of back pain and adult degenerative deformity. Neurosurgery **63**, 191–196 (2008)
8. Wang, M.Y., Anderson, D.G., Poelstra, K.A., Ludwig, S.C.: Minimally invasive posterior fixation. Neurosurgery **63**, 197–203 (2008)
9. Cobb, J.: Outline for the study of scoliosis. Instructional Course Lectures **5**, 261–275 (1948)
10. Haddas, R., Xu, M., Lieberman, I., Yang, J.: Finite element based-analysis for pre and post lumbar fusion of adult degenerative scoliosis patients. Spine Deformity **7**, 543–552 (2019)
11. Shuman, B.R., Goudriaan, M., Desloovere, K., Schwartz, M.H., Steele, K.M.: Muscle synergies demonstrate only minimal changes after treatment in cerebral palsy. Journal of Neuroengineering and Rehabilitation **16**(46) (2019)
12. Nazifi, M.M., Hur, P., Belanger, T.A., Boah, A., Haddas, R., Lieberman, I.H.: The effect of surgical alignment on gait complexity in adult deformity patients: a neuromuscular synergy approach. The Spine Journal **18**(8), 130 (2018)
13. Clark, D.J., Ting, L.H., Zajac, F.E., Neptune, R.R., Kautz, S.A.: Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. Journal of Neurophysiology **103**(2), 844–857 (2010)
14. Combs-Miller, S., Dugan, E., Beachy, A., Derby, B., Hosinski, A., Robbins, K.: Physiological complexity of gait between regular and non-exercisers with parkinson's disease. Clinical Biomechanics **68**, 23–28 (2019)

15. Chen, Y., Hu, H., Ma, C., Zhan, Y., Chen, N., Li, L., Song, R.: Stroke-related changes in the complexity of muscle activation during obstacle crossing using fuzzy approximate entropy analysis. Frontiers in Neurology **9:131** (2018)
16. Ting, L.H., Macpherson, J.M.: A limited set of muscle synergies for force control during a postural task. Journal of Neurophysiology **93**(1), 609–613 (2005)
17. Nazifi, M.M., Yoon, H.U., Beschorner, K., Hur, P.: Shared and task-specific muscle synergies during normal walking and slipping. Frontiers in Human Neuroscience **11**(40) (2017)
18. Nazifi, M.M., Beschorner, K.E., Hur, P.: Association between slip severity and muscle synergies of slipping. Frontiers in Human Neuroscience **11**(536) (2017)
19. Nazifi, M.M., Beschorner, K.E., Hur, P.: Do walking muscle synergies influence propensity of severe slipping? Frontiers in Human Neuroscience **13**(383) (2019)
20. Chvatal, S.A., Torres-Oviedo, G., Safavynia, S.A., Ting, L.H.: Common muscle synergies for control of center of mass and force in nonstepping and stepping postural behaviors. Journal of Neurophysiology **106**(2), 999–1015 (2011)
21. Hur, P., Pan, Y.-T., DeBuys, C.: Free energy principle in human postural control system: Skin stretch feedback reduces the entropy. Scientific Reports **9**(1), 16870 (2019)
22. Hur, P., Shorter, K.A., Mehta, P.G., Hsiao-Wecksler, E.T.: Invariant density analysis: Modeling and analysis of the postural control system using markov chains. IEEE Transactions on Biomedical Engineering **59**(4), 1094–1100 (2012)
23. Hur, P., Duiser, B.A., Salapaka, S.M., Hsiao-Wecksler, E.T.: Measuring robustness of the postural control system to a mild impulsive perturbation. IEEE Transactions on Neural Systems and Rehabilitation Engineering **18**(4), 461–467 (2010)
24. Pan, Y.-T., Yoon, H.U., Hur, P.: A portable sensory augmentation device for balance rehabilitation using fingertip skin stretch feedback. IEEE Transactions on Neural Systems and Rehabilitation Engineering **25**(1), 31–39 (2010)
25. Friston, K.: The free-energy principle: A unified brain theory? Nature Review Neuroscience **11**(2), 127–138 (2010)
26. Bisi, M.C., Stagni, R.: Complexity of human gait pattern at different ages assessed using multiscale entropy: From development to decline. Gait & Posture **47** (2016)
27. Nazifi, M.M., Beschorner, K., Hur, P.: Angular momentum regulation may dictate the slip severity in young adults. PLoS One **15**(3), 0230019 (2020)
28. Haddas, R., Sikora-Klak, J., Mar, D., Kisinde, S., Block, A., Lieberman, I.: The value of overall assessment in adult degenerative scoliosis patients: short-and long-term effect of surgical intervention on static and dynamic balance, gait and pain level. Spine Deformity **9**, 33 (2021)
29. Farina, S., Tinazzi, M., Pera, D.L., Valeriani, M.: Pain-related modulation of the human motor cortex. Neurological Research **25**(2), 130–142 (2003)
30. Hodges, P.W., Jull, G.A.: Spinal segmental stabilization training. In: Liebenson, C. (ed.) Rehabilitation of the Spine: A Practitioner's Manual, pp. 585–611. Lippincott Williams & Wilkins, Baltimore, MD (2007). Chap. 25
31. Hodges, P.W.: Pain and motor control: From the laboratory to rehabilitation. Journal of Electromyography and Kinesiology **21**(2), 220–228 (2011)
32. Hodges, P.W., Moseley, G.L.: Pain and motor control of the lumbopelvic region: Effect and possible mechanisms. Journal of Electromyography and Kinesiology **13**(4), 361–370 (2003)
33. Lund, J.P., Donga, R., Widmer, C.G., Stohler, C.S.: The pain-adaptation model: a discussion of the relationship between chronic musculoskeletal pain and motor activity. Canadian Journal of Physiology and Pharmacology **69**(5), 683–694 (1991)
34. Rudolph, K.S., Eastlack, M.E., Axe, M.J., Snyder-Macklere, L.: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. Journal of Electromyography and Kinesiology **8**(6), 349–362 (1998)

Figures

Figure 1 Two generic muscle synergies with high EnIM (a) and low EnIM (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.

Figure 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.

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

Table 1 Required number of walking synergies pre- and post-surgery, and t-test results.

	Pre-surgery	Post-surgery	p-value
Number of synergies (Mean ± SD)	4.46 ± 1.33	5.07 ± 1.44	0.04

Table 2 Entropy of each walking muscle 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

Figures

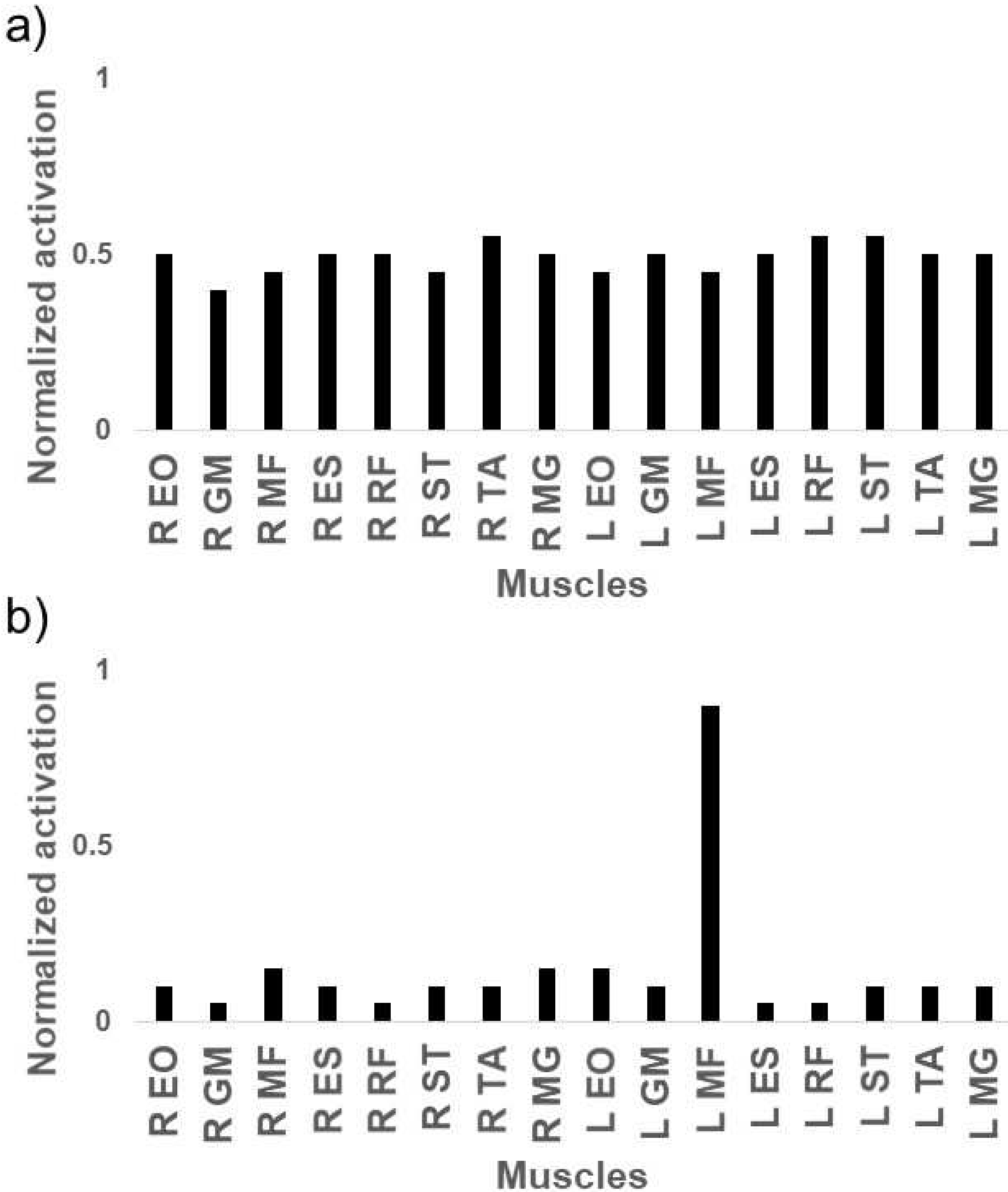

Figure 1

Two generic muscle synergies with high EnIM (a) and low EnIM (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.

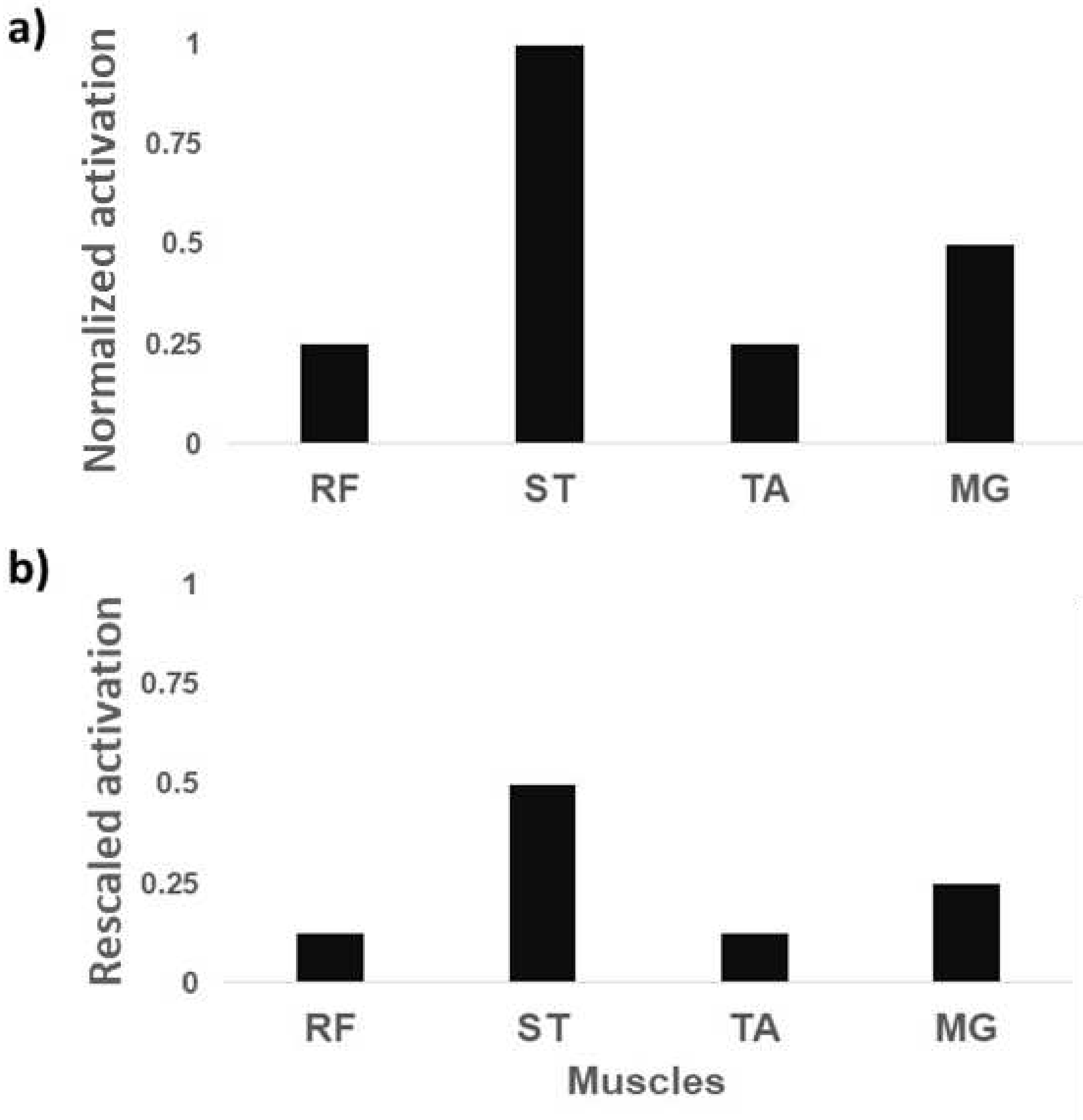

Figure 2

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.

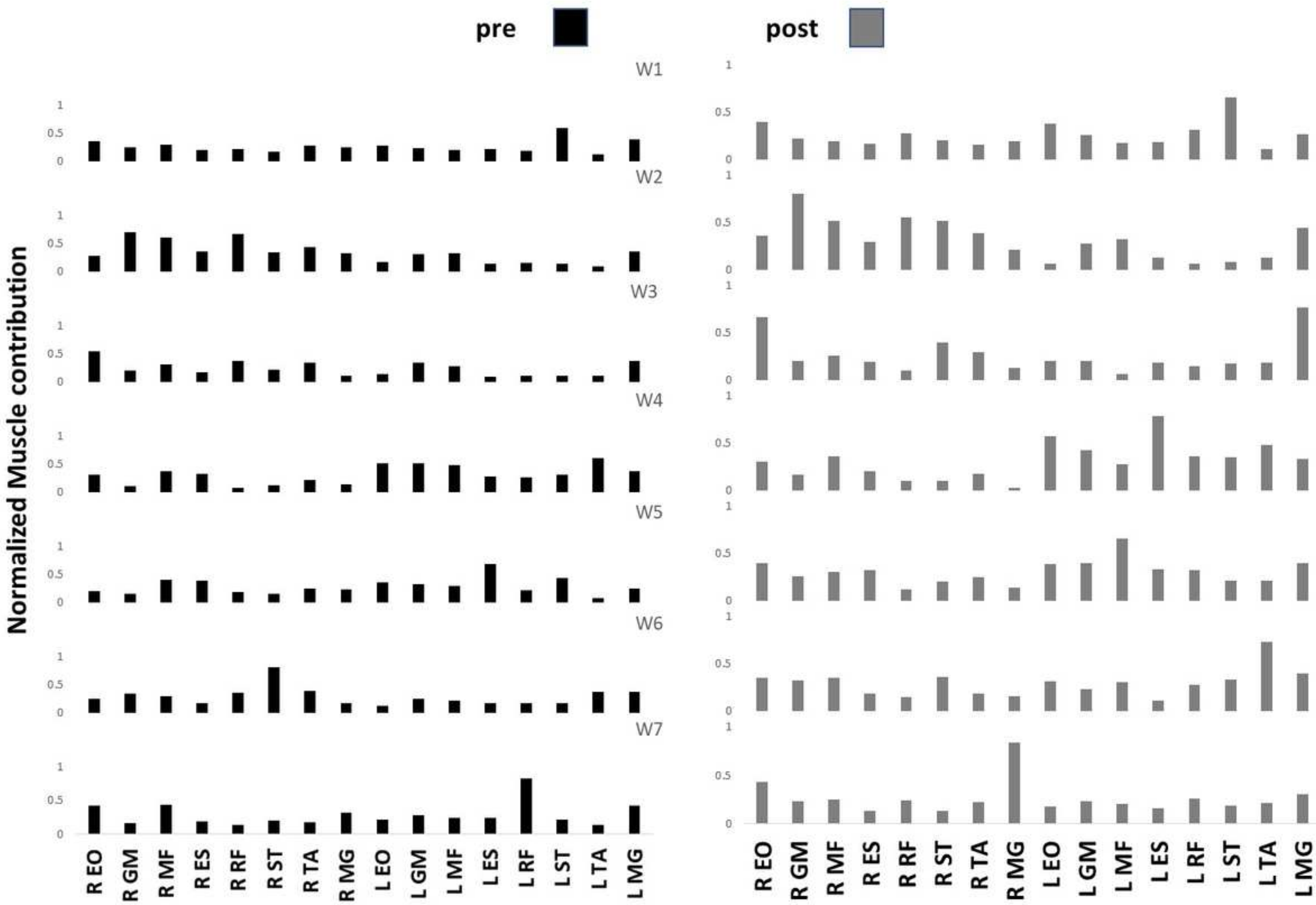

Figure 3

Pre- and Post-surgery walking muscle synergies.