Proficiency-based recruitment of muscle synergies in a highly perturbed walking task (slackline)

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Summary
In neurophysiology, a hypothesis under investigation relates to how neural modularity helps in learning of skills. Accordingly, we studied differences in muscle synergy (MS) organization at three different proficiency levels on a task more challenging than walking. Our study included slackline walking whereby the perturbations to evoke postural responses are generated by the participants rather than externally controlled. Furthermore, studying MS of individuals with different proficiency levels under such constraints will provide us an understanding of different strategies for dynamic postural stability. Hence, the main aim of our study is to identify MS associated with proficiency during slacklining. Muscle Synergies and their activation coefficients were extracted using factor analysis on electromyography that was recorded from lower limb muscles. The spatial and temporal profiles were analyzed to examine muscle co-activation patterns for stability across three different groups of slackliners (high, moderate, and nonproficient). We found three robust MS structures across all skill levels associated with crouched gait while slacklining. Higher activation of quadriceps, gastrocnemius, and hamstrings with tibialis anterior was observed for synergy one, two, and three, respectively. An additional proficiency-based synergy was recruited for highly proficient slackliners, and similarly for nonproficient ones. For highly proficient slackliners, the additional synergy was in relation to lowering of the center of mass for consistent stabilization. For nonproficient slackliners (PS), the recruitment of additional synergy was related to consistent knee flexion with the higher range of motion. Overall, our work showed alteration in the modular organization of MS at different proficiency levels that could be associated with differences in knee kinematics during slacklining. We think that the outcomes of our study regarding differences in the MS organization based on proficiency levels, and the underlying neuro-physiological features, will facilitate rehabilitation of individuals with balance disorders.

KEYWORDS
muscle synergies, crouched gait, slacklining, EMG, knee, proficiency
1 | INTRODUCTION

Understanding postural control strategies is crucial for human locomotion and other gross motor skills. Studies have suggested that walking on a challenging support surface while maintaining balance control causes a more arrhythmic gait pattern within a subject, making it more difficult to understand coordinated activation of the muscles to maintain stability. Researchers have suggested robust muscle co-activation schemes underlying postural control which may be modularly organized as muscle synergy (MS), aka movement primitives. Previous studies have provided substantial evidence of these building blocks existing in the central nervous system (CNS) using intracortical microstimulation, N-methyl-D-aspartate (NMDA) iontophoresis, and cutaneous stimulation. Moreover, the MS (spatial profiles) and their recruitment coefficient (temporal profiles) are generally extracted from electromyography (EMG) signals and are of significant interest in motor control. The combination of these modularly organized motor primitives leads to diverse motor behavior and, analyzing MS may provide information about specific muscle co-activation patterns on a fundamental functional level for posture control.

In the field of neuroscience, there is limited understanding for skill dependent changes in the modular behavior as most studies focused on the modular changes for impaired motor function. Some studies have previously shown augmentation and emergence of new synergies in vertebrates across different biomechanical events. However, these investigations do not present the effect of motor learning/skill levels on the MS dimensional space or its structure during a task that imposes greater kinematic constraint in the anteroposterior (AP) direction during walking, and offers greater degrees of freedom in the mediolateral (ML) direction at the same time. Such specific task dynamics gives us a unique perspective on neuromuscular strategies for stability as ML instability is very common among elderly and cerebral palsy. Therefore, we aim to examine different skill levels and the effect on the modular behavior for postural stability using the MS hypothesis on a slacklining task.

It is a daunting task to understand how the MS are combined to stabilize posture within individuals of different proficiency levels during a complex motor task. Bernstein’s (1967) hypothesis on reduction in the degrees of freedom addresses MS hypothesis suggesting that from an infinite set of solutions the CNS selects a relatively standard motor solution to accomplish a task which could also include maintaining a stable posture. Moreover, postural control among highly skilled individuals is developed over years of learning and training. Previously, the solution space or MS has shown adaptations to simplify control during learning, since it represents internal joint/muscle coordinates for a specific task and these elements can be updated with skill acquisition. Shadmehr and Ivaldi also observed changes in the MS underlying spinal circuitry with respect to a newly learned task. It is believed that MS are combined to form a low-dimensional motor solution from a high-dimensional space of available motor primitives to simplify the motor control problem. Therefore, it is possible that decomposition of EMG signals into synergies vectors and their respective activation coefficients will render us a relationship between proficiency levels and the number of MS utilized for postural control.

The central objective of our study is to identify proficiency-based MS for stability employing a task that poses greater kinematic constraint in the AP and more kinematic degrees of freedom in the ML direction than normal walking. Hence, we utilized a slackline to study the differences in the modular behavior between a group of individuals with different levels of balance-related task proficiency (high, moderate and nonproficient slackliners, NPS, the latter requiring some assistive support). Furthermore, the imbalance to evoke a postural response were generated by the controller (participant) himself/herself rather than externally controlled. The Muscle Synergies are generally associated with biomechanical function hence understanding proficiency-based synergy in a challenging condition to attain stable balance will likely provide us different neuromuscular strategies to accomplish task level goals effectively. In our study, the challenge was to maintain a stable posture/balance during walking on a slackline which typically has considerable variability in postural sway in the ML direction. This behavior is also typically observed among individuals with neurological disorders. Therefore, understanding proficiency-based neuromuscular strategies on slackline can be useful for designing rehabilitation interventions of neuromotor deficits.

It is important to understand the biomechanical response of proficiency-based MS. Our study also focuses on identifying such relationships between kinematics, synergy structure and their recruitment profiles. Regarding kinematics, we know that human walking is a more complex system than an inverted pendulum since it is regulated by the CNS; thus, having higher kinematic degree of freedom in ML direction does not narrow the effect of kinematics in AP direction. Therefore, the mapping of kinematics for stability in the AP direction was considered in this study. Also, previous studies have already examined the coordination strategy in ML direction for the same task. Furthermore, on comparison between slacklining and walking from our previous study, we identified alterations in the muscle co-activation patterns
during slacklining.\textsuperscript{1} The muscles groups that were altered mostly associated with balance control along the AP direction. Based on these rationales we examined the kinematics and muscle kinetics in AP direction in this study.

We tested two hypotheses in our study. First, we hypothesized that similar MS structures were recruited by the modulation of their recruitment profiles across each individual. Second, we hypothesized that based on the proficiency level, different number of MS across the groups would be recruited. To test our hypotheses, we compared the number of synergies (dimensional space) and its structure (composition of muscle loadings in the synergy space) across three different skill levels: PS, moderately proficient slackliners (MPS), and NPS. We compared the extracted synergies using FA across these groups to determine changes in the synergy structure as each synergy represented neurophysiological features for task performed. Our results show differences in the dimensional size of synergies with respect to different levels of proficiency. The additional synergy recruited in PS and NPS was considered as group specific/proficiency-based synergy.

The main contributions of our paper are as follows:

- We study postural control in a novel balancing task that involves subject-induced perturbations on slackline.
- We present the differences in synergy dimensional space with respect to the different level of proficiency with multiple trials for each participant.
- We relate the synergistic activation of muscles corresponding to postural kinematics for stability to identify biomechanical function.
- We identify changes in proficiency based MS supporting maintenance and enhancement of postural stability on slackline.

2 | MATERIALS AND METHODS

The study was approved by the Institutional Review Board of University of Arkansas at Little Rock under protocol number 17098 and 18097. Nineteen healthy individuals, right leg dominant participated in the study by signing a consent form.

2.1 | Experiment design and data collection

All participants underwent standard skin preparation (eg, hair removal, cleaned with alcohol etc.) for EMG acquisition prior to data collection. The electrical activity of the muscles was recorded using a Noraxon Telemyo direct transmission system (DTS) with wireless sensors at the sampling rate of 1500 Hz. The Ag/AgCl dual snap electrodes with an inter electrode distance of 2 cm were placed on the surface of the skin at the belly of nine different muscles identified by palpation. Each site corresponded to different muscles from different fascial compartments of the thigh (anterior, posterior and medial) and lower leg (anterior and superficial posterior). The muscles for this study included: Vastus Medialis VAS (M), Vastus Lateralis VAS (L), Rectus Femoris (RF), Gastrocnemius Medialis GAS (M), Gastrocnemius Lateralis GAS (L), Semitendinosus (ST), Biceps Femoris (BF), Gracilis (GR) and Tibialis Anterior (TA). Although the trunk and hip muscles contribute toward stability, they were not directly included in the study because the muscles contributing toward their extension and flexion had already been included. Also, two dual-axis Noraxon Electrogoinometers, one to record hip flexion angle and another to record knee flexion angle, were utilized. The goniometers were placed in the sagittal plane. For knee joint measurement, one block end of the device was placed at lower thigh and another end at the shank. For hip, one end of the device was placed at the trunk and another at the upper thigh. The sampling rate for goniometers data acquisition was also 1500 Hz. The task included walking on a six meter taut elastic slackline. The height of the unweighted slackline was maintained at 0.61 m above ground thus maintaining the strain. The displacement of the line was quantified by the Noraxon triaxial accelerometer at a sampling rate of 1500 samples per second with sensing axes oriented toward Mediolateral (ML) for X, Anteroposterior (AP) for Y and Vertical (V) for Z coordinates. A foot switch was used to identify the heel strike and toe off instances. We identified the gait events (heel strike and toe off) from foot switch data by visual inspection and a code was written on R to record the indexes of the gait events. A schematic diagram of our experimental protocol is shown in Figure 1. The EMG, accelerometer, and goniometers data were acquired using myoresearch XP software that integrates our devices with similar sampling rate and thus automatically syncs the data.
FIGURE 1  Schematic diagram of our experimental design. A. The slackline random perturbations are generated by the participant in V, ML, and AP directions. B. shows the anterior and posterior view of leg muscles location where electrodes were placed to acquire electromyography using direct transmission system transmission receiver (F) which is also synchronized with footswitch (C) and twin axis goniometers (D) to track gait cycle and knee/hip joint kinematics. E shows the acquired data for a single gait cycle. All the devices were synchronized at similar sampling rate. The shaded region represents stance whereas the rest shows swing.

2.2  Sample size, proficiency, and statistical tests

A longer slackline is more challenging as the participant has to cover more distance in an erratic dynamic environment. Hence, to determine the level of proficiency of slackliners, and sample space, three different length slacklines were introduced (30.5, 15.24, and 6 m). Five participants that were able to comfortably walk on 30.5-, 15.24-, and 6 m slacklines were categorized as PS. Two were able to finish 15.24 and 6 m task, ranking near higher proficiency scale and were also categorized as PS. A smaller group of individuals in the study were able to learn the task and were able to walk on the 6-m slackline with proper balance ranking near moderate proficiency. A total of five participants were categorized as MPS. The rest (seven participants) were novices who were given slight assistance by experimenter’s finger loosely cuffed around their wrist to complete the task and thus were considered as NPS.

Generally it took 10 to 14 steps (5-7 gait cycle/trials) to complete the task on the 6-m slackline. On an average 5 to 7 gait cycles which comprised EMG, kinematic (via electrogoniometers, foot switch) activities were collected from each participant as 5 to 7 gait trials (A single gait cycle = One trial/Gait trial).

A power analysis of variance (ANOVA) test was performed to determine the number of gait trials (strides) required in the study for three different proficiency levels to detect an effective sample size. It was found that 38 trials were needed for each group of three different proficiency levels, power of 0.9, a significance level of 0.01 with large effect size of a Cohen value of 0.4. Therefore, sufficient number of gait trials (5-8 trials per participant) were collected so that each group has 40 gait trials/cycles. A total of 120 (40 × 3) trials were collected for highly skilled, moderately skilled, and NPS with assistive support.

2.3  Preprocessing and data analysis

R programming language and its packages were used for EMG preprocessing and analysis. The EMG signal from each channel was bandpass filtered with a fourth order Butterworth type filter. The critical frequencies for the filter were from
20 to 500 Hz. The signals from the channels were demeaned, their amplitudes were normalized between 0 and 1 using Equation (1) for each participant, and rectified moving average (MA) value of the signals was computed with a moving window of 100 ms without overlap. The gait cycles were identified by the visual inspection of the foot switch signal. EMG signal for each gait cycle were later time normalized (spline interpolation) to 1000 time points for each individual. The normalization of EMG signal was performed as follows:

\[ X_i = (x_i - \min(x))/\left(\max(x) - \min(x)\right) \]  

(1)

Here, \( x \) represents the EMG channels, \( X_i \) is the normalized data at each (\( i \)th) time point for a participant.

For accelerometer signal, the DC offsets and outliers were removed and signals for each axis were smoothed using MA with a nonoverlapping window of 500 ms.

### 2.4 Dimensional space with PCA

Principal component analysis was performed on EMG matrix size (9 \( \times \) 1000) for each gait trial (40 \( \times \) 3) and the variance accounted for each component was computed for every single gait trial. Prior ensemble averaging of gait trials was avoided as it might affect the variance and covariance structure of the data set.

After identifying the number of components/synergies that accounted 90\% variance for each gait trial across the PS, MPS and NPS group, a kernel density estimation was performed to estimate the probability density function (PDF) of the number of components/synergies across the groups. The number of components estimated across "PS,e NPS and MPS were later defined in FA and was considered as the number of synergies to be extracted. The multichannel EMG signals were then decomposed by FA for synergy extraction. Each vector in the extracted dimensional space by FA comprises of the weights or loadings of muscle activations. Later, we performed analysis on these extracted spatial profiles (synergies) using cosine correlation and, for temporal profiles (activation coefficient) using zero-lag cross correlations.

### 2.5 Synergy similarity and ordering

The extracted synergies did not have a predefined sequential order. Thus, selecting a reference participant and synergy ordering was necessary to identify similar synergies.\(^\text{24}\) The synergies extracted for each participant were ensemble averaged for their comparison and ordering. Later, a reference participant was randomly selected. Then, for initial sorting, the cosine correlation value (\( r \)) across the rest of the participant’s synergies was computed with respect to the reference participant’s synergies. After referencing and computing \( r \) values for synergy vectors across the rest of the participants, ordering of synergies was performed. We performed ordering of the synergies based on their \( r \) values using MS ordering scheme given in Table 1. A threshold \( r \) value based on previous studies was defined to differentiate shared and group specific MS.\(^\text{2, 24}\) A pair of synergies were considered similar with \( r > .7 \), marginally similar with \( .7 > r > .45 \), and dissimilar for \( r < .45 \).\(^\text{24}\) The methodology for the ordering of similar MS is given in Table 1.

In our ordering scheme, a total of four synergies were compared between the test group and reference participant that resulted in 16 correlation values. Each synergy vector of a reference participant was compared with four synergy vectors of a test participant resulting in four \( r \) values for each synergy vector of a reference participant compared. Thus, a vector of 1 \( \times \) 16 was formed.

For synergy ordering, the sorting algorithm identified the max \( r \) value from the four combinations of each synergy vector of reference participant with the test group. Later, the respective row number was identified. For example: for synergy one (\( r_{1,1} \)), once the maximum \( r \) value was identified, the respective row number was removed and not used for ordering. In short, if synergy one was highly correlated with synergy three of test participant, the synergy three of the test participant was not compared anymore in the ordering scheme and we moved to synergy two ordering and the steps were repeated again. The activation coefficients were ordered in relation to their respective MS.

### 2.6 Kinematic data

To find the physiological relevance of the underlying MS, knee and hip angles were measured and analyzed. Generally the knee and hip joints are either flexed or extended due to an individual’s posture or placement of electrogoniometers when
recording the kinematic data. The additional extension or flexion angles offset the kinematic data resulting in observation of additional knee and hip extension/flexion values during slacklining. Therefore, a reference trial for each individual was acquired to measure the degree of extension or flexion for its removal from subsequent trials.

In a reference trial the participants were asked to stand overground. The data was recorded for a duration of 2 to 3 seconds. The mean values of angles from the reference trial were later used to remove the offset from knee and hip angles during slacklining.

### 2.7 Statistics

A histogram plot is used to plot the frequency distribution of the accelerometer data to quantify the variability in the task. The dispersion in the accelerometer data suggest higher level of perturbation.
An $\alpha$ value of 0.01 was considered for statistical significance in our study. Power ANOVA test was used to determine the number of trials needed to be collected in our study and a $t$ test was used to compare the kinematics and activation coefficients between groups that reveal difference in neuro-muscular strategy.

For higher loading values, a threshold value of 0.6 in a synergy space was considered as a significant contributor to that MS. $^{25}$

## 3 | RESULTS

### 3.1 | Dynamics of the task

The accelerometer data was analyzed to get an idea about the perturbations. Moreover, this data also showed that the slackline walking was consistently performed with respect to the experimental protocol, as study participants do not perform a bounce walk. The amplitude of the accelerometer signal from the ML plane showed higher variability than other directions (Figure 2).

An F test performed between ML-AP and ML-V direction showed statistical significant difference between them ($P < .01$). Also, by definition a kinematic degree of freedom of a system is the number of independent variables that ascertain the position of a system. Thus, more variability in the ML plane suggests that the task provides more kinematic degree of freedom in the mediolateral direction and higher kinematic constraint in the anteroposterior direction.

### 3.2 | Number of extracted synergies

For synergy analysis, we first identified the number of MS with the threshold method as explained in the methodology Section 2.4. We found that the number of synergies explaining maximum variance for each gait trial varied due to trial by trial variability as observed from the foot switch signal. The identified synergy number for each individual’s gait trial were pooled corresponding to each group’s proficiency level. Later, a kernel density estimation was performed on that data. The kernel density estimation was used to estimate the PDF. From the PDF plot we identified the maximum likelihood of the number of synergies needed to be extracted for PS, MPS, and NPS. The kernel density estimation showed that mostly four synergies were recruited for PS and NPS; whereas, for MPS, three synergies were recruited. Figure 3 shows the number of synergies recruited for each of the groups using kernel density plot. Thus, the number of synergies differed across different proficiency levels.

**FIGURE 2** Frequency distribution showing variability in the acceleration of the slackline (perturbations) during slacklining. The mediolateral plane exhibited most variability than the anteroposterior and vertical plane.
3.3 Shared and group-specific muscle synergies

We then aimed to identify similar MS associated with shared motor behavior from our MS ordering scheme. We found similarities in most of the synergy vectors with respect to the reference participant. The first three synergies were more similar across the participants but the fourth synergy for PS and NPS was marginally similar. On an average for synergy one, two, three and four, the $r$ values were $0.84 \pm 0.06$, $0.84 \pm 0.08$, $0.81 \pm 0.12$, and $0.59 \pm 0.16$, respectively. The extracted synergies and their respective coefficients for PS, MPS, and NPS are shown in Figure 4.

The additional synergy recruited for PS and NPS was categorized as group-specific/proficiency-based MS, shown in Figure 6. Table 2 shows the dimensional space similarity for each group. Further, we found that the activation coefficients of MS that were similar across all participants displayed lesser degree of similarity.

The zero-lag cross-correlation of activation coefficients between reference participant was also computed to find changes in MS recruitment. On an average, the $r$ values of $0.45 \pm 0.05$, $0.23 \pm 0.06$, $0.13 \pm 0.05$, and $0.06 \pm 0.05$ across temporal profiles of participants suggested a weak correlation for similar/shared synergies. Therefore, consistent to our hypothesis most of the MS were preserved across the participants with different proficiency levels although their respective temporal profiles had a weaker correlation.

3.4 Motor function of shared MS

Each synergy vector can be associated with a specific motor function that contributes toward stability during slacklining. To understand the functional role of each synergy vector shared across the participants in each group, synergy vectors and their activation coefficients were averaged and muscles with loading values $\geq 0.5$ were analyzed. The activation profiles were also studied to understand their role towards postural stability. Figure 4. displays a comparison of shared synergies suggesting co-activation of different groups of muscles. Figure 4 also shows the shared synergies with their respective activation coefficients.
Averaged shared muscle synergies across participants; B, with their respective activation coefficient. The shaded region shows SE

| Reference synergy | P2 | P3 | P4 | P5 | P6 | P7 | M ± SD | P8 | P9 | P10 | P11 | P12 | M ± SD | P13 | P14 | P15 | P16 | P17 | P18 | P19 | M ± SD |
|-------------------|----|----|----|----|----|----|--------|----|----|-----|-----|-----|--------|----|----|-----|-----|-----|-----|-----|--------|
| Group             | PS | MPS | MPS | MPS | MPS | MPS | MPS    | MPS | MPS | MPS | MPS | MPS | MPS    | MPS | MPS | MPS | MPS | MPS | MPS | MPS | MPS |
| 1                 | 0.87 | 0.91 | 0.95 | 0.87 | 0.89 | 0.73 | 0.87 ± 0.07 | 0.84 | 0.71 | 0.92 | 0.83 | 0.87 | 0.83 ± 0.07 | 0.83 | 0.78 | 0.82 | 0.94 | 0.91 | 0.80 | 0.79 | 0.84 ± 0.06 |
| 2                 | 0.90 | 0.80 | 0.85 | 0.92 | 0.80 | 0.61 | 0.81 ± 0.10 | 0.84 | 0.96 | 0.7 | 0.85 | 0.91 | 0.85 ± 0.09 | 0.8 | 0.85 | 0.86 | 0.90 | 0.95 | 0.85 | 0.87 | 0.87 ± 0.04 |
| 3                 | 0.88 | 0.78 | 0.81 | 0.89 | 0.87 | 0.78 | 0.84 ± 0.04 | 1.00 | 0.78 | 0.8 | 0.66 | 0.91 | 0.83 ± 0.11 | 0.43 | 0.93 | 0.74 | 0.82 | 0.90 | 0.84 | 0.89 | 0.8 ± 0.16 |
| 4                 | 0.56 | 0.48 | 0.49 | 0.74 | 0.74 | 0.52 | 0.59 ± 0.11 | 0.79 | 0.44 | 0.54 | 0.6 | 0.74 | 0.28 | 0.81 | 0.6 ± 0.18 |

We found from synergy one and its activation coefficient a higher loading of muscles (VAS(M) = 0.92 ± 0.04), (VAS(L) = 0.99 ± 0.03), and (RF = 0.67 ± 0.03) during the stance phase for postural stability. The structure of synergy two and its activation coefficient suggested its association with stabilization of the foot during the mid and terminal stance phase due to high loading values of (GAS(L) = 0.9 ± 0.03), (GAS(M) = 0.67 ± 0.04), and (ST = 0.61 ± 0.04) muscles. From the third factor loading values and respective activation profile, synergy three could be associated with stabilization of the hip by its extension and adduction as higher loading values of (BF = 0.9 ± 0.02), (ST = 0.5 ± 0.03), (GR = 0.67 ± 0.02), and (TA = 0.9 ± 0.03) prior to swing phase were observed. Synergy four being marginally shared revealed group-specific or proficiency-based changes in the synergy structure. Thus, synergy I, II, and III across groups showed specific co-activation of quadriceps, hamstrings and lower limb muscles, respectively, for stability.

### 3.5 Gait kinematics on a slackline

We proceeded to identify the slackline gait kinematics to better understand relationship between joint angles and shared motor behavior for postural stability. The kinematics for each gait trial were identified using foot switch signals and then ensemble averaged for each group. A kinematic relationship across PS, MPS, and NPS was also analyzed using
TABLE 3  Correlation of hip and knee angle for proficient slackliners (PS), moderately proficient slackliners (MPS), and nonproficient slackliners (NPS) averaged kinematic gait trial

|            | MPS Knee angle | NPS Knee angle | MPS Hip angle | NPS Hip angle |
|------------|----------------|----------------|---------------|---------------|
| PS Knee angle | 0.91           | 0.61           |               |               |
| PS Hip angle  | 0.80           | 0.81           |               |               |

Figure 5  A, Knee joint angles showing higher flexion for “PS” than “MPS” and “NPS”; B, Schematics of fully extended knee and hip joint showing upright posture; C, Schematic diagram of crouched gait posture displaying higher knee and hip flexion

correlation analysis. We found higher knee (32° ± 4°) and hip flexion (160° ± 5.18°) for slacklining than the overground reference trial. Further, PS (36.59° ± 7.1°) and MPS (32.29° ± 7.6°) revealed higher knee flexion than NPS (27.18° ± 5.7°). However, NPS flexion was more consistent and significantly different ($P < .01$) than MPS with a higher range of motion. The consistency in flexion was based on the standard deviation value.

The knee angle displayed a lesser correlation between PS and NPS, whereas hip angle was similar across the groups. This weaker correlation between PS and NPS may suggest the role of variable knee kinematics toward recruitment of additional synergy and variability in their structure across PS and NPS. Table 3 shows ($r$) for the hip and knee for PS, MPS and NPS. A higher knee flexion and hip flexion for PS, MPS, and NPS is a characteristic of crouched gait for postural stability as shown in Figure 5.

3.6  Motor function of group-specific MS

Synergy four being marginally shared had a variable composition of muscle loadings. We aimed to identify changes in synergy loadings for PS and NPS in relation to their motor behavior. We found that synergy four displayed alterations in Quadriceps, BF and GR. Higher loading values for BF (0.73 ± 0.14) and GR (0.65 ± 0.09) were observed for PS, whereas NPS showed a higher factor loading for only GR (0.66 ± 0.03) and BF (0.61 ± 0.11). Moreover, the activation coefficient timing of synergy four within a group was not consistent and the amplitude was statistically significant between both groups ($P < .01$). This modulation in the recruitment profile within a group and between groups may likely suggest the recruitment of additional marginally shared MS.

In comparison with NPS (as shown in Figure 6), peak recruitment activity for PS was observed at the stance and during the swing phase resulting in higher loading of Quadriceps, BF, ST, and GR. However, the activation coefficient of synergy
FIGURE 6  Comparison of synergy four and their temporal profile for proficient slackliners (PS) and nonproficient slackliners (NPS). A, Muscle distribution in synergy space four for PS represented with purple and for NPS is represented with black color; B,C, shows their respective averaged activation coefficient for gait trials/cycle. The shaded region shows SE. An increased activation is observed during the swing phase for NPS in comparison with PS four for NPS showed lower factor loadings than PS during the stance resulting in lower loading of quadriceps and BF. Moreover, for NPS, a higher activation coefficient than PS at the swing phase likely resulted in higher loading of GR. A higher loading value of GR could be associated with consistent knee flexion during a full gait cycle. Thus, an additional synergy was observed depending on the proficiency level. The exhibited alterations in the additional synergy structures could be associated with proficiency based neuromuscular strategy to meet the demand for stability.

4 | DISCUSSION

We studied modularity in the dimensional space during slackline walking among groups with proficiency level (PS/MPS/NPS). Our results suggest that the number of MS and the synergy structure varied with different proficiency levels. An additional group-specific/proficiency-based synergy emerged for PS and NPS. The recruitment of group-specific/proficiency-based synergies was associated with knee kinematics. We determined three synergies were shared with higher similarity across PS, MPS, and NPS. The fourth synergy was recruited with less similarity for PS and NPS only. The synergies that were shared/robust between the groups suggest motor functions in relation with controlled foot response and crouched gait for the postural stability on the slackline. The additional less similar synergy for PS and NPS were categorized as group-specific/proficiency-based MS. We also observed that knee angles showed a significant difference in PS and NPS. This suggests that the additional synergy is associated with an increased knee flexion for PS. Moreover, for NPS, lower but considerably consistent knee flexion is attributed with the recruitment of synergy four.

Quantifying motor learning in a postural stabilization task is challenging. In previous studies, lesser sample space for trials,²⁶,²⁷ simple postural task constraints and scoring system,²⁷ and models, which may not be as highly challenging for novices¹⁰ were used to study the effects of motor learning on MS. A more challenging task that provides greater variability in the mediolateral direction was employed in this study with the intent that it may impose kinematic changes in relation to muscle co-activation.¹⁰,²⁷ It has been previously observed how unstable gait conditions between different population groups modulates activation timing of muscles in relation with kinetics and kinematics.²⁸,²⁹,³⁰ Our study is consistent with the previously mentioned studies which showed higher variability in timing and amplitude of EMG response during the task for well trained individuals. We have also observed modulation in timing and amplitude of MS recruitment. This may have resulted in alteration of modular organization suggesting different postural strategies for stable posture.³¹ Our study is novel in presenting skill-dependent changes in the number of MS. Furthermore, a consistent number of synergies were also observed for NPS and PS when active assistive support was given to the NPS. Our results were similar to what was reported for spinal cord injury patients with assistive devices when compared with the control group.³²
We classified individual's skill level using multiple parameters. The experience of performers, consistency in their performance during the experiment, and different slackline platforms were considered. Also, our investigations were performed on a significantly larger sample size across each group. However, intra-subject variability across participants will exist even across PS. Therefore, grouping of individuals was needed and based on the above-mentioned criteria the participants were classified into three proficiency levels.

The synergy analysis was performed on each gait cycle/trial. Our work showed that each gait cycle/trial exhibited a different number of synergies. However, these MS were similar in terms of structure across the participants or groups for stability on the slackline. The changes in the sensory inflow at each gait cycle imposed by biomechanical constraints resulted in not just flexible recruitment of synergies, but also alteration in modular organization. Hence, variability in the EMG activation from the postural response underly synergistic activation of the muscles rather than independent activation. Therefore, we employed a probability density estimate to identify the number of synergies across each group comprising of the gait trials as a different number of synergies were observed for each trial within a group. The different number of synergies across each group may correspond to different neuromuscular strategies for stability. Also, our MS ordering algorithm scheme revealed the robust synergy structures across participants. The presence of higher number of shared MS across participants thus suggested shared motor behavior.

We found in our study that the synergy recruitment profiles for robust synergies displayed less similarity as additional synergies were recruited for NPS, the PS. This suggests that rather than altering the structure of MS due to modulation in the recruitment profiles of PS and NPS, the PS and NPS recruit an additional synergy to maintain stability on slackline. The alteration in the synergy recruitment did not affect the synergy structures across groups or individuals. This supports the hypothesis that synergies across the participants were consistent even though the synergy recruitment exhibited alterations. Overall, our study supports the notion that sensory inflow increases within subject variability and reduces the motor output to a common set of solutions or shared motor behavior across the participants. However, proficiency-based variability in motor solutions do exist and increases an individual's ability to efficiently accomplish task level goals. We thus conclude that the changes in the number of synergies and their structure with difference in proficiency levels aided to accomplish task level goals. The new proficiency-based synergies may have emerged as a larger set of solutions to accomplish the task among PS and NPS. However, further investigation is required, particularly in the case of NPS and MPS as to how training will optimize the synergy structure and dimensional size.

4.1 Neurophysiological inference

The notion of kinematic synergies provides an approach to quantify the covariation of elemental variables for a task. In our study, we found specific muscle co-activation patterns that displayed relationships with respect to kinematics. We observed that for shared and proficiency-based synergies, the motor function was to stabilize the posture with a crouched gait and controlled foot response. The additional synergy was related to lowering the center of mass for stability by bending the knee since quadriceps and pes anserinus (ST and GR) muscle group were co-activated in PS as explained by higher knee flexion. The knee flexion was more consistent in NPS than MPS. Also, the recruitment of synergy four displayed peak recruitment activity during the swing phase unlike PS activation coefficient. A higher range of motion than PS may have prompted this behavior resulting in higher activation of GR. Thus, the additional synergy showing higher activation of GR in relation with consistent knee flexion and its higher range of motion contributed towards stability. Although, our study suggests the role of knee kinematics and its association with recruitment of GR in additional synergy space for stability, it is limited to presenting its role in the sagittal plane. However, GR role as a hip adductor and its relation with the range of motion in the frontal plane will open more prospects to understanding hip and knee kinematics for additional synergy recruitment. Therefore, in the future GR and other muscle's role in stability across different groups can be assessed in the frontal plane.

4.2 Kinematics in AP over ML

Although the dynamics of the task shows higher variability in the ML direction, we have studied the kinematic relationship of MS in the AP direction since MS has previously shown alteration in muscles that are primarily involved in AP stability. Our result shows that even with perturbation along the ML direction, individuals adjust knee kinematics to stabilize the posture by flexion. This suggest that the CNS does not only regulate joint kinematics with respect to higher
perturbation direction for stability, but rather based on a specific neuromuscular strategy. Although, not examined in this study, kinematics in ML direction can be crucial and have been previously studied.\textsuperscript{20} The learning period has shown that the trunk and foot oscillations were dampened in the ML direction over training and leading to coordinated movement of elbow joints.\textsuperscript{20}

Since our study focuses on the lower limb muscles and our previous work had shown alteration of muscles coordination primarily associated with AP stability, therefore, we investigated changes in MS and its biomechanical response in relation to kinematics in the AP direction.

### 4.3 Modular size hypothesis

In this subsection, we present the consistency of our hypothesis with respect to our results and supporting it with previous studies. Researchers have observed alteration in modular organization not only among neuromotor deficits but also among skilled individuals.\textsuperscript{10,34,39,40} From our investigation we suggest that skill dependent changes or long-term training may increase the modular space of synergies, thus increasing the set of motor solutions or neuromuscular strategies to efficiently control posture.\textsuperscript{34} Moreover, a slight assistive support for nonslackliners may have provided higher range of motion for knee joint, thus increasing the motor solutions for NPS hence recruiting additional synergy. Sawers et al have suggested the same conclusion, but their study did not show a significant difference in the kinematics among experts and novices.\textsuperscript{10} It is likely that the slackline, although more challenging than beam walking, provides greater kinematic freedom in the mediolateral direction, therefore kinematic changes in MS were observed. However, an argument can be made on this hypothesis based on the consistency of modular organization observed during walking with perturbation.\textsuperscript{41,42} We believe that for natural motor behavior like walking, years of learning and training encode the information in the CNS to maintain stability during perturbations.\textsuperscript{3} Therefore, the tuned neuro-muscular strategy to maintain a stable posture may likely not show any changes in the MS dimensionality. Furthermore, assessing the modular organization without learning will also not show any significant difference in the MS dimensionality. Therefore, our study is the first to present such modular changes in relation to changes in kinematics for efficient postural control across three different groups.

### 4.4 Clinical implications

In this subsection, we discuss the clinical relevance of our study. As seen earlier, several perturbing platforms in AP and ML directions had been used to study the reactive balance.\textsuperscript{43,44} Moreover, the adaptation to motion in one planar requires postural control in other planes as well.\textsuperscript{43} Therefore, it is crucial in clinical studies to be specific in terms of plane orientation to study the reactive balance. We believe that slackline as a task can be useful in clinical studies to study reactive balance control. Also, the perturbations were generated by the participants rather than externally generated.

The instability in ML direction is one of the leading causes of fall in elderly and in patients with neurological disorders.\textsuperscript{13,43} The use of a slackline suggests the significance of our study in identifying patterns of muscle co-activation for effective postural control and avoiding fall.\textsuperscript{44} Moreover, slackline as a sport may assist individuals in developing postural response that requires stability in a similar challenging situation.\textsuperscript{1} A higher knee flexion kinematic responses to lower the Center of Mass (COM) is one such behavior that was observed previously to provide knee stability in forward motion.\textsuperscript{1}

The results from our study showed changes in the dimensionality of MS for three different groups on a novel task. Therefore, training on a slackline may improve the postural stability among individuals affected with ML instability by incorporating new synergies. However, as suggested earlier, it remains to be investigated how these new synergies evolve over time. In terms of activation and kinematics our results do show the specific muscle co-activation patterns associated with greater stability in ML plane. This may provide new prospects in the field rehabilitation therapy for training-specific groups of muscles.

## 5 CONCLUSION

We conclude that modular organization of MS differed during slackline walking across different proficiency levels. Shared motor behavior existed resulting in crouched gait and additional proficiency-based synergies emerged in both PS and NPS. For PS the additional synergy indicated higher knee flexion; for NPS consistent knee flexion and higher range of motion were associated with the additional synergy to more efficiently meet the task specific goals.
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