

Alteration of muscle synergy structure while walking under increased postural constraints

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Abstract: It is hypothesised that specific groups of muscles aka muscle synergies (MSs) are combined by the central nervous system to control a wide repertoire of movements and also simplify motor control. Therefore, studying MSs during human locomotion is of significance, as it may reveal neuromuscular strategies for postural stability. In this study, the authors aimed to use the hypothesis of MSs to identify specific muscle co-activations during overground walking and slacklining where postural perturbations were generated by the participants rather than being externally controlled. Nine participants were asked to walk overground and on a slackline while they recorded myoelectric activity of their leg muscles. They extracted synergies from the electromyography signals in the two tasks using factor analysis. The results showed adaptation in the shared MSs structure during walking on the slackline and these shared MSs across participants were recruited flexibly to meet the demand for stability. The modulation of synergies suggests adaptive neuromuscular strategies for stability while walking on a slackline. Specifically, higher activation of quadriceps during slacklining suggests a crouched gait to facilitate balance. During overground walking, lower leg muscles revealed higher activation compared to slacklining to support a more consistent toe-off during the stance phase.

1 Introduction

Muscle synergies (MSs) have been hypothesised to be the building blocks for a wide range of motor behaviours. The modular motor structures that underpin synergy activations have been shown to be organised in the central nervous system [1]. These encoded modules are combined linearly to enable performance of various movements [2, 3]. Therefore, MS analysis may provide a better understanding of neuromuscular strategies or specific muscle co-activation to perform a movement.

Postural adjustments are crucial to accomplishing motor tasks successfully especially while walking. However, during a sudden increase in neuromechanical constraints, it is not clear how muscles are activated synchronously to establish a stable posture and avoid fall. Identifying such muscle co-activation may provide aspects that are crucial for the rehabilitation of neuromotor deficits. Thus, studying MS by evoking a postural response of individuals can provide the synergistic activation of muscles for stable posture to avoid fall and can be useful for rehabilitation purposes.

In the last decade or so, simple perturbing platforms have been used to investigate neuromuscular strategies employing the MS hypothesis for stability [4–7]. These research studies utilised a number of experimental protocols to understand specific muscle co-activation for postural stability under different task conditions or induced perturbations [4, 6–9]. However, one limitation of MS studies associated with balance control [4, 5, 7] is their use of externally controlled platforms. Also, loss in balance control among postural disorders is neurological instead of arising from external shifts in the walking surface. Hence, we introduced slacklining, a novel intricate neuro-mechanical task that requires a constant balancing act on a narrow elastic surface. More importantly, the perturbation in this task is generated by the participants themselves. We examined changes in the MS by applying it to the slackline condition, where perturbations are dependent on the controller (i.e. the participant) and overground walking [10].

The aim of our study is to understand potential adaptations of MS during walking on a complex neuromechanical task because studying synergies during balance/walking on such an intricate task can further our understanding about the role of specific MS in postural adjustment. Previously, it was observed that consistent MSs were recruited even though the timing in muscle activation patterns or activation coefficients varied during walking in different conditions [11, 12]. The hypothesis of our study is based on the similar concept of flexible recruitment of a robust synergy structure. We hypothesised that the MS used by the participants will be similar in the two tasks suggesting the existence of spatial patterns of muscle activity shared across tasks, although the way they are recruited may differ depending on task constraints.

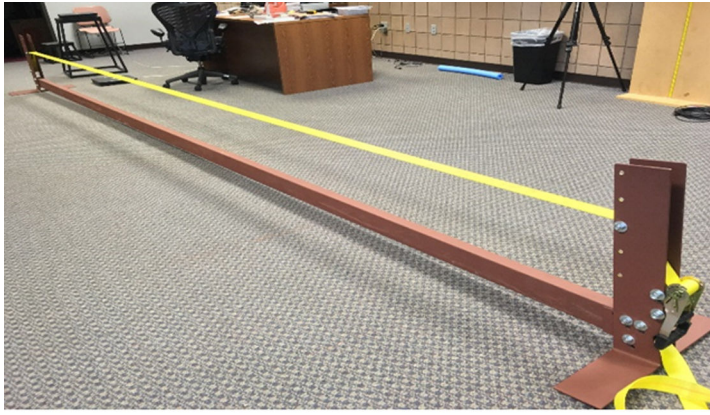
In this study, we have found evidence for task-specific modulation of synergies for postural stability. The quadriceps and hamstrings muscles showed alteration in their structure while slacklining in comparison with overground walking. Also, lower leg muscles were less activated during slacklining than overground walking. We believe that these observed changes in the structures of synergies arose to provide stability.

2 Methodology

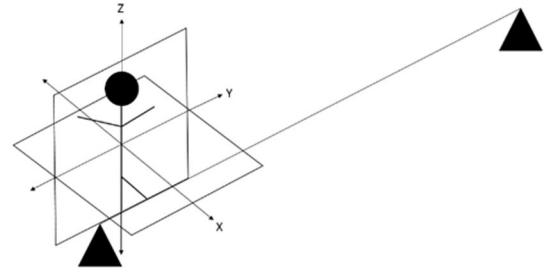
This study was approved by the Institutional Review Board of the University of Arkansas at Little Rock (UA of Little Rock) under protocol number 17-098. Nine participants (four males and five females) volunteered for the research and signed a consent form. Two of them were well-experienced slackliners (one male and one female) and were used as a reference group in the study for similarity comparison whereas the novices were included in the test group.

2.1 Experimental design

The protocol for data collection involved the following tasks: (a) walking on the ground from point A to point B (21 feet) at a self-selected pace (0.5 ± 0.18 m/s); and (b) walking on a 19-foot



a



b

Fig. 1 The setup used to examine muscle synergies while slacklining

(a) A 19-foot slackline prototype with a height of 0.46 m from the ground used in our study, (b) Schematic illustration of slackline walking along the X, Y, and Z coordinates

slackline at the height of 0.46 m over the ground. The line sag measured in the middle of the slackline was kept in the range of 0.2–0.25 m. Novices with no previous slacklining experience were trained for 20–30 min to balance on the slackline. Two to four learning trials (also mentioned as test trials) were recorded from each volunteer until the participants were able to perform at least one full gait cycle on the line. On the final trial, participants completed the task with scant support. The slackline model used in our lab and schematic diagram of the slackline are shown in Fig. 1.

2.2 Electromyography (EMG) recording

Noraxon Telemetry direct transmission system (DTS) (Noraxon USA Inc.) was used with wireless sensors to acquire EMG data. Nine silver/silver chloride (Ag/AgCl) snap electrodes with a self-adhesive area of 4 cm × 2.2 cm and an interelectrode distance of 1.75 cm were used. A DTS footswitch with two force sensors was attached to the forefoot and heel of the participants to monitor heel strike and toe-off during walking. Nine muscles of the dominant leg (i.e. right leg) were targeted: vastus medialis (VAS(M)), rectus femoris (RF), vastus lateralis (VAS(L)), gracilis (GR), tibialis anterior (TA), gastrocnemius medial (GAS(M)), gastrocnemius lateral (GAS(L)), bicep femoris (BF), and semitendinosus (ST). The EMG signals were acquired at 1500 Hz. To measure perturbations of the slackline, a Noraxon DTS triaxial accelerometer was fixed in the middle of the slackline with the axes oriented towards the mediolateral (ML), anteroposterior and vertical (V) directions.

2.3 Data processing & analysis

Surface EMG (sEMG) signals were recorded from the point when the participant mounted the slackline until the completion of the task. The signals from each channel were filtered with a second-order high pass Butterworth filter with a cut-off frequency of 20 Hz [13]. We then rectified the filtered EMG signals and computed the root-mean-square envelope (with a 200-ms non-overlapping window) using the R biosignal EMG package [14]. The EMG envelope for each channel was further normalised to peak values as suggested by the authors of [15, 16]. Cubic spline interpolation was performed to equate the sEMG signal length to 1000 time points to remove any length-based biasing of the signal [17].

2.4 Extraction of MSs

Linear decomposition algorithms are used to extract MS from the EMG data [3, 18]. The mathematical model of synchronous MS includes N synergy vectors \mathbf{W}_i , each activated by a single time-varying coefficient C_i as

$$\mathbf{X}(t) = \sum_{i=1}^N C_i(t) \cdot \mathbf{W}_i \quad (1)$$

We used factor analysis (FA) to determine C and \mathbf{W} from the EMG data [19]. The dimensionality of control commands differs from the state space of the musculoskeletal structure [10]. Hence, it is crucial to determine the synergy subspace accurately. Principal component analysis was used due to its better performance compared to the commonly used non-negative matrix factorisation algorithm [19]. The Kaiser–Meyer–Olkin (KMO) test was performed on the sEMGs of each individual to check the adequacy of the sample size for FA. The minimum KMO value for our data was 0.63 and the highest was 0.81. All the datasets qualified based on the KMO criterion for FA that requires a threshold >0.6. Bartlett's test for sphericity was performed to test for orthogonality of each muscle activation. For each volunteer, the correlation matrix diverged from the identity matrix ($p < 0.001$).

2.5 Weighting coefficients and similarity across participants

The MS vectors contain the relative loadings of activity across all muscles. To quantify the similarity of synergies across participants based on orientation rather than magnitude, cosine similarity (CS) was used. It is the ratio between the scalar product of the Euclidean norms of the two vectors (i.e. cosine of the angle between them) [20]. The equation for CS is shown below for vectors \mathbf{x} and \mathbf{y}

$$\cos(\mathbf{x}, \mathbf{y}) = \frac{\mathbf{x} \cdot \mathbf{y}}{\|\mathbf{x}\| \cdot \|\mathbf{y}\|} \quad (2)$$

There is no specific threshold for CS to validate the similarity but a value close to 1 is considered highly similar and a value close to 0 is considered dissimilar [7, 8, 21]. A zero-lag cross-correlation metric was further used to analyse the similarity between the weighting coefficients (i.e. temporal patterns of synergy activation) across participants.

2.6 Choice of reference participants

The extracted synergies are compared across participants. Thus, sorting out a reference participant is crucial [7]. The proficient slackliners were identified as reference participants in this study (Ref^a, Ref^b). The synergy structures represent neuromechanical features of a movement. Therefore, to capture and compare the proper dynamics of the task, selecting proficient slackliners was an appropriate choice. We compared synergies of each proficient slackliner with those of the remaining participants using CS to generate similarity spaces.

In general, we found that a lesser number of dimensional subspaces were shared for the slacklining task in comparison with walking. The shared synergies between two tasks that were identified using reference participant^a and reference participant^b, an F -test was performed on them. The significantly different synergies from the F -test were classified as task-specific synergies.

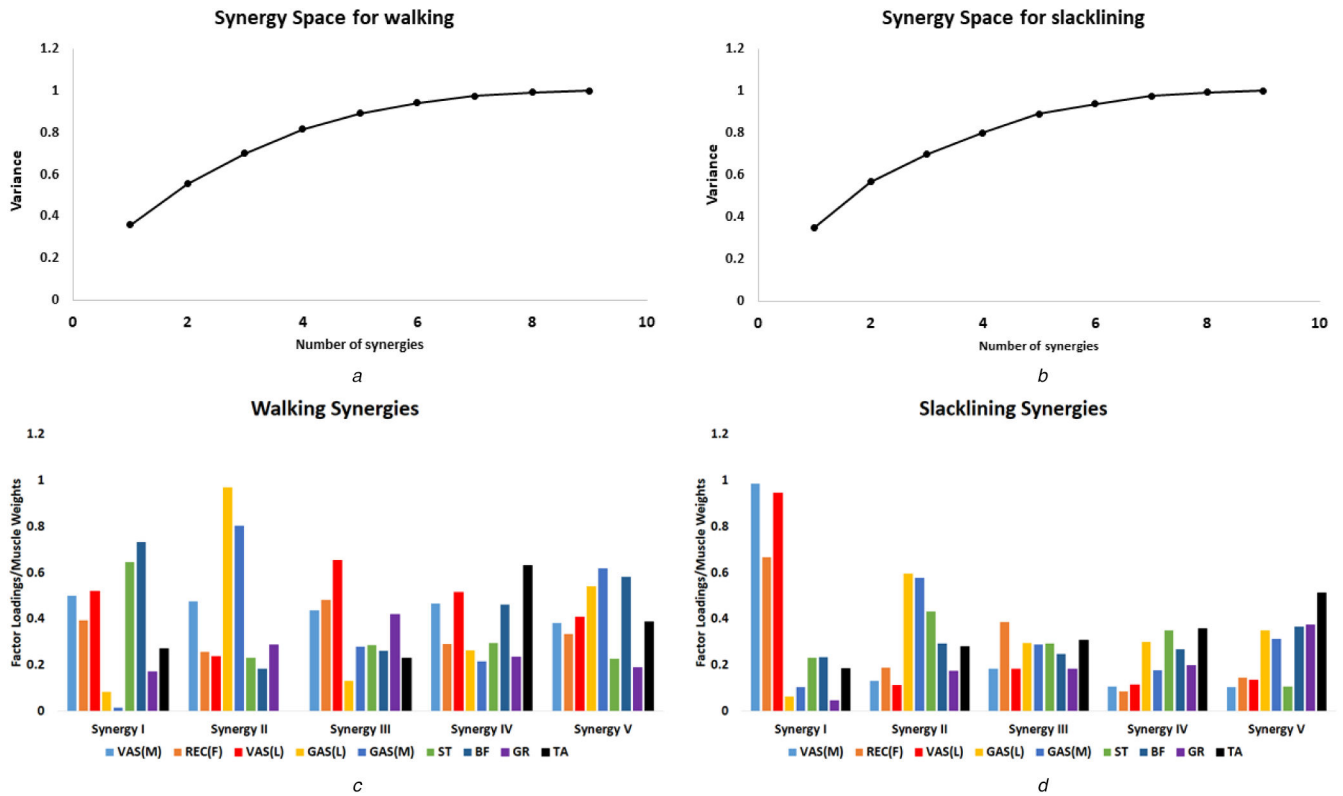


Fig. 2 Five factors were sufficient to explain $\geq 90\%$ variance on average for (a) Slacklining, (b) Walking (black curves in the figures) across the participants, (c) Muscle contribution of each muscle for all the extracted synergies while slacklining across participants. VAS(M), REC(F), and VAS(L) showed the highest activation in synergy I, GAS(M) and GAS(L) were mainly activated in synergy II, (d) Average loading of muscles for extracted synergies while walking across participants. GAS(M) and GAS(L) showed the highest activation among shared synergies I and II

Table 1 Number of MS shared while walking and slacklining across participants

Participant	Synergies shared walking							
	One	Two	Three	Four	Five	Six	Seven	Eight
reference ^a	3	5	5	4	3	3	4	4
reference ^b	4	3	5	5	3	5	5	3

Participant	Synergies shared slacklining							
	One	Two	Three	Four	Five	Six	Seven	Eight
reference ^a	3	3	3	3	2	2	3	2
reference ^b	3	1	3	2	1	1	4	3

3 Results

3.1 Exact number of synergies

First, we aimed to determine the number of MS underlying each task. We found that for both slacklining and walking, six out of seven participants used five synergies. A low-dimensional space with five synergies explained an average variance of 90% across individuals while any additional synergy accounted for $<5\%$ variance. For both movements, a total of five synergies were extracted for further evaluation and analysis (Fig. 2). The average weights of MS across the participants for both movements are shown in Fig. 2.

3.2 MSs contribution towards walking

We then aimed to identify which of the above synergies were common across individuals and the biomechanical purpose they serve. To test this, we computed CS to compare the synergy vectors between the reference group and the rest of the participants and also analysed their temporal profiles to understand the activation pattern (discussed in Section 3.6). The number of shared synergies

categorised by CS between all novices and the two reference participants is shown in Table 1.

We found that synergy I was shared with $r \geq 0.77$ and synergy II with $r \geq 0.9$ was highly shared across participants for walking (both statistically significant with $(p < 0.05)$). The average loading of TA across all the five factors was low and GR activation was less consistent across participants throughout the synergy space (Fig. 2d). In the shared synergy space, synergy I revealed consistent activation for quadriceps group of muscles ((VAS(M) = 0.61 ± 0.14), (VAS(L) = 0.54 ± 0.13), (RF = 0.51 ± 0.15)) and high co-activation of hamstring group of muscles (BF = 0.64 ± 0.16) and (ST = 0.73 ± 0.13). The relatively similar loadings of both quadriceps and hamstrings group of muscles explain their role towards forward motion during walking [10]. Moreover, synergy II showed consistently high co-activation of (GAS(L) = 0.86 ± 0.10) and (GAS(M) = 0.74 ± 0.11) suggesting their role towards foot propulsion. Thus, each synergy explained the biomechanical function of each muscle group towards walking.

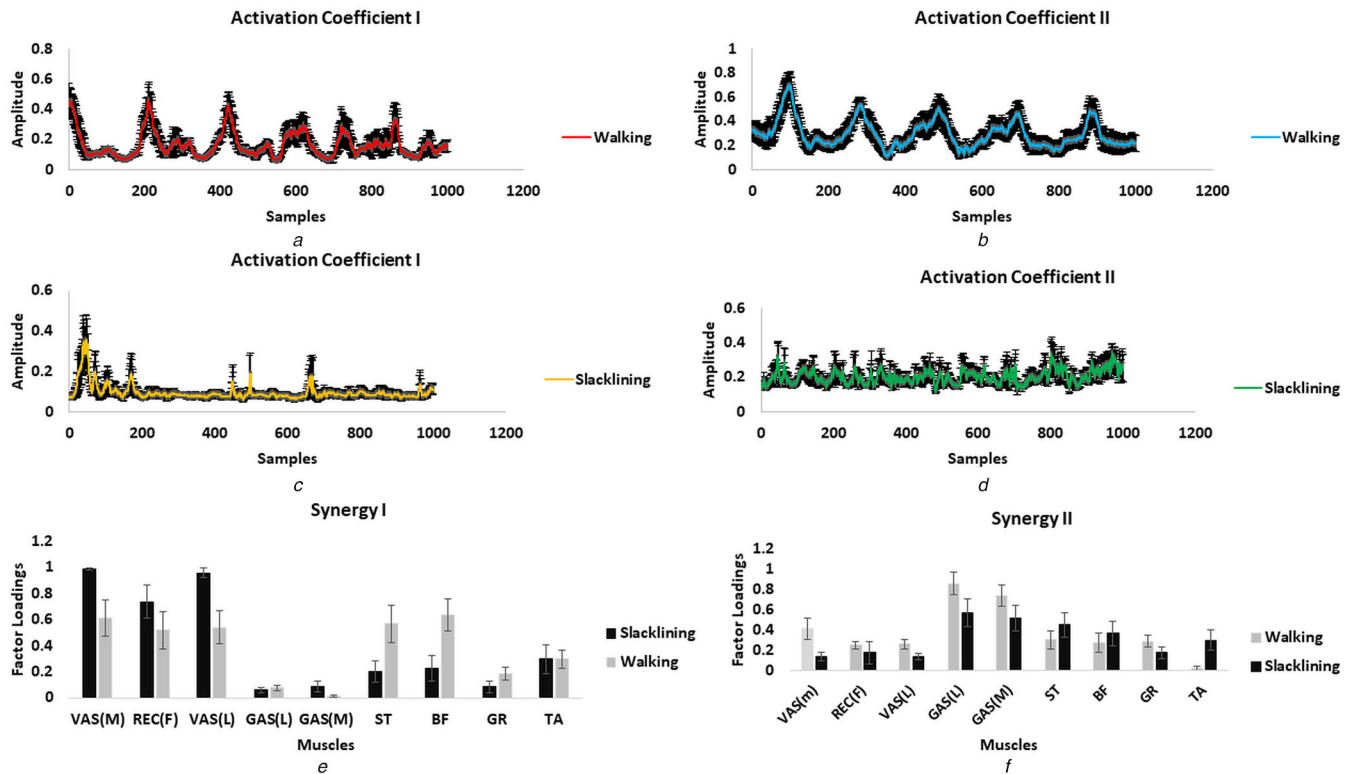


Fig. 3 Activation coefficients of synergies I and II while

(a), (b) Walking, (c), (d) Slacklining. The temporal profile shows more rhythmic activity of walking than slacklining as the stance and swing are more distinguishable, the grey region represents standard error, (e), (f) Task specific modulation of synergies I and II for walking and slacklining

Table 2 Quadriceps factor loading during test trials for shared synergies

Muscles	Factor loadings of participant				
	One	Two	Three	Four	Five
VAS(M)	0.84 ± 0.06	0.66 ± 0.33	0.87 ± 0.12	0.77 ± 0.17	0.71 ± 0.21
REC(F)	0.7 ± 0.15	0.45 ± 0.18	0.91 ± 0.08	0.51 ± 0.40	0.72 ± 0.17
VAS(L)	0.99 ± 0.01	0.65 ± 0.31	0.75 ± 0.15	0.99 ± 0.01	0.34 ± 0.03

3.3 MSs contribution towards slacklining

We then aimed to identify the modular behaviour and role of different synergies towards slacklining. Similar to walking, we used CS to identify the shared slacklining MSs across participants and analysed their respective activation coefficient (discussed in Section 3.6). The extracted synergies for slacklining are shown in Fig. 2c; Table 1 shows the synergies that were identified as shared across participants. For the full range of the slacklining task, synergy I and synergy II were shared between the reference group and the rest of the participants ($r \geq 0.9 \pm 0.04$ and $r \geq 0.7 \pm 0.09$).

A higher TA, which indicates dorsiflexion, was also observed during slackline walking throughout the extracted synergy space (0.33 ± 0.05). Furthermore, knee flexors (VAS(M) = 0.98 ± 0.01), (RF = 0.73 ± 0.12) and (VAS(L) = 0.95 ± 0.04) were highly activated in the synergy I. A crouched gait was observed during slacklining and this was accompanied by higher activation of knee flexors. Also, synergy II displayed relatively higher activation of the lower leg and hamstring muscles than any other muscle group, though with lower consistency, namely (lateral = 0.59 ± 0.14 & medial gastrocnemius = 0.57 ± 0.13), and (ST = 0.50 ± 0.12), as shown in Fig. 2. The recruitment of GAS(M), GAS(L), and hamstrings together but at relatively lower activation suggests a less prominent push off response of lower leg muscles while slacklining. Thus, suggesting the role of different muscle groups towards slacklining.

3.4 Modulation of MS across tasks

To understand if the participants used the same synergies to perform both walking and slacklining, we compared the extracted

synergies between the two tasks. The synergy similarity spaces for shared synergies were significantly different ($p < 0.05$) between tasks, suggesting that the synergies were task-specific and were modulated by task dynamics. The modulation in the composition of the muscle weights from walking to slacklining can be observed from their relative loadings as shown in Fig. 3. In particular, the quadriceps and hamstrings activations were significantly different ($p < 0.05$) for the shared synergies between movements.

3.5 Inter-trial consistency of MSs during slacklining

To establish the consistency of the extracted MSs, we compared the synergy structure during the test trials besides comparing synergy structures for the full task movement during slacklining. We found MS structures were preserved across participants and thus revealed a consistent modular structure of the motor output, in agreement with our hypothesis. The test trials also showed higher co-activation of quadriceps (VAS(M) = 0.68 ± 0.1), (RF = 0.61 ± 0.09), (VAS(L) = 0.81 ± 0.07) than any other muscle group (see Table 2).

3.6 Temporal profiles and flexible control

We then aimed to examine if the temporal activations of the two synergies were similar across participants. To assess this, we computed the similarity of the corresponding activation coefficients of synergies I and II for both walking and slacklining. Even though walking showed a weak zero-lag correlation between the reference group and the rest of the participants, it was still significantly more correlated than the slacklining temporal profiles as displayed in Table 3. An F -test showed significantly different ($p < 0.01$) synergy activations between walking and slacklining. More

Table 3 Zero lag correlation of activation coefficients across participants

	One	Two	Three	Four	Five	Six	Seven	Eight
slacklining								
activation coefficient I ^a	-0.06	-0.01	-0.05	-0.03	-0.037	-0.037	-0.05	-0.05
activation coefficient II ^a	-0.0081	0.02	-0.109	0.106	-0.054	0.03	-0.13	0.016
activation coefficient I ^b	-0.03	0.77	-0.05	0	0.34	0.07	-0.15	0.67
activation coefficient II ^b	0.001	-0.07	-0.109	0.08	-0.09	-0.03	-0.08	0.05
walking								
activation coefficient I ^a	0.17	0.27	0.21	0.24	0.15	0.10	-0.05	0
activation coefficient II ^a	0.57	0.61	0.77	0.56	0.43	0.44	0.07	0.01
activation coefficient I ^b	-0.08	0.18	0.21	0.27	0.33	0.26	-0.07	-0.01
activation coefficient II ^b	0.47	0.56	0.77	0.46	0.44	0.64	-0.05	0.02

importantly, the zero-lag correlation of the temporal profiles of different participants was significantly higher for walking than slacklining ($p < 0.05$). Fig. 3 shows the temporal profile for synergies I and II while performing both movements.

Specifically, the activation coefficients of synergies I and II exhibited more arrhythmic activity during slacklining compared to walking as shown by the temporal profiles. Usually, temporal profiles associated with the recruitment of GAS are more pronounced during the stance phase, as this muscle is responsible for forward propulsion during the second half of stance [22–24]. During the swing and stance of each gait cycle, the temporal activation of synergy II became more arrhythmic especially near the middle of the slackline. This resulted in inconsistent recruitment of GAS, whereas the temporal profile of synergy I showed consistent temporal recruitment of VAS(M), VAS(L), and RF across participants for slacklining.

4 Discussions and implication

We investigated a novel task, i.e. slacklining to understand the role of increased neuromechanical constraints on locomotor behaviour. Slacklining is a unique neuromechanical task where perturbations are generated by the performer rather than externally controlled [4, 7]. We found alterations in synergy composition between overground walking and slacklining due to the increased biomechanical constraints. Also, most of the synergies were more similar during walking than slacklining. We have also found quadriceps revealed higher activation whereas GAS muscles were less co-activated during slacklining than walking. Moreover, quadriceps and hamstrings muscles showed changes in their activation between the two tasks.

Several studies have combined walking and perturbation surface models to understand the effect of biomechanical constraints on the emergence of synergies [4, 5, 7]. In these studies, a motor adaptation of balance was studied using perturbations that were mechanically constrained to limited directions while position and magnitude were controlled externally. In our study, perturbations were generated by the participants themselves rather than externally controlled. Also, walking on a slackline provides greater positional and directional variability in ML direction. Therefore, studying MS on such a platform gave us a unique understanding of modular behaviour associated with postural control as opposed to the unconstrained context.

We found that five synergies, two of which were task-specific, were sufficient to explain 90% of the variance in muscle activity for both tasks. Inter-subject analyses indicated that most synergies during walking were consistent across participants [25]. However, we observed the emergence of more dissimilar structures during slacklining [7, 26]. This is consistent with what is suggested by Torres and Ting [7] that apart from the recruitment of pre-existing modules, new synergies may emerge with a full range of movement.

A within and between task intra-subject variability in the synergy subspace is to be expected due to lower-level muscular demands as the stepping rhythm varied across individuals during slacklining to meet the demand of postural stability [11, 12]. This

may have resulted in a higher number of subject-specific MSs [27–29]. On the other hand, lower variability in EMG data is an outcome of movement with lower variability in gait pattern, i.e. overground walking [30]. Thus, for overground walking we found higher inter-subject MS consistency compared to slacklining [29–31]. This can be seen from the more consistent temporal activations of the walking synergies. In short, the composition of MS, but not their temporal recruitment, was consistent across participants. Furthermore, temporal correlations were higher for walking compared to slacklining. A possible explanation for this is that, during complex motor tasks such as slacklining, the sensory inflow may have altered the recruitment and structure of the MSs while stabilising posture [21].

The alteration in the sensory inflow is generally associated with changes in the temporal or activation coefficient pattern, which modulates the synergy structures [12]. We think that the differences in the sensory feedback level across different gait cycles for each participant arising due to task dynamics may be resulting in such changes in the sensory inflow [7, 32]. The synergy structure here represents the composition of the muscles in each synergy vector. It was reported previously that during human locomotion on the unsteady platforms, alterations of temporal profiles were related to the supraspinal structure, which modulates the composition of MS [12]. However, our study does not present a relationship between descending commands and temporal profiles, but based on our results it suggests that the changes in the task dynamics have altered the activation coefficients and respective synergy structures by possibly changing the sensory feedback, inflow mechanism, and/or limb biomechanics for stability [1]. This was verified in mice where the absence of feedback affected the spatial (MS) and temporal structures (activation coefficient) but not their numbers [33]. Overall, our results suggest that shifting from lesser challenging tasks to a task that requires higher postural control, the synergy structures were altered to meet the demand for stability. Moreover, during the learning trials with one to two gait cycles and lesser task variability, we observed recruitment of pre-existing modules. Although, with successful completion of the slacklining task changes in the synergy structure were observed, which were likely an outcome of the alteration in sensory inflow and/or modified limb biomechanics due to the changing task dynamics.

4.1 Neurophysiological relevance of synergy I

The functional role of VAS(M) and VAS(L) is to stabilise and extend the knee whereas RF (apart from extending knee) also flexes the hip while walking. However, while slacklining, to maintain balance, participants appeared to adopt a crouched gait resulting in higher knee flexion. It is thus reasonable to have higher co-activation of the quadriceps group of muscles during slacklining compared to normal walking.

4.2 Neurophysiological relevance of synergy II

Synergy II activating mainly GAS(M) and GAS(L) had the highest consistency across participants for walking. However, for slacklining synergy II displayed the comparatively less consistent

activity of GAS(M) and GAS(L). The quadriceps and hamstrings muscles in synergy II showed different activations between walking and slacklining. Analysis of the footswitch data revealed that the stance phase had a longer duration during slacklining, suggesting more time was utilised to achieve postural balance on the slackline. Additionally, initial foot strike in early stance and toe-off in terminal stance were not as prominent in slacklining as in walking. The less defined toe-off phase and longer duration of the midstance phase could be the reason for the lower activation of GAS(M) and GAS(L) and higher activation of TA when compared to normal walking.

4.3 Differences in synergy structure between walking and slacklining

We found that, for both tasks, synergies I and II were associated with balance and control. However, their muscle weights differed between the two tasks. Slacklining synergy I displayed a high contribution to the quadriceps muscles. On the other hand, co-activation of the quadriceps and hamstrings were observed in walking synergy I. For synergy II, higher co-activation of GAS(M) and GAS(L) muscles were present while walking. Overall the loadings of VAS(M), VAS(L), RF, ST, and BF were altered when walking on the slackline, as shown in Fig. 3. This suggests the task-specific modulation of synergies. Regarding their functional roles, synergy I appeared to explain knee stability and synergy II indicated a more pronounced push-off response of GAS(M) and GAS(L) during slacklining.

4.4 Future work

In this study, we observed differences in MS structures between slacklining and walking. Specifically, quadriceps and hamstrings for both movements varied within the synergy space. The higher activation of quadriceps could possibly be due to the bending of the knee as a stability mechanism to avoid loss of balance. Lower co-activation of plantar flexor muscles is likely due to inconsistent toe-off timing in comparison with the walking synergy II, which might result from a dynamically unstable surface.

A previous study [34] suggested slackline as a novel exercise to enhance quadriceps recruitment, core strength, and balance control. Another study on isometric back squat exercises [35] showed a higher co-activation of the same muscles with a 90-degree angle. Our results indicate that slacklining similarly elicits synergistic co-activation of quadriceps as in isometric back squat. Moreover, a study on mild crouched gait [36] reported results that are consistent with our study. This can lead us to a future investigation using motion sensors to understand the role of crouched gait towards stability on such a surface which serves as a crucial physiological marker among postural disorders such as cerebral palsy [37]. This research may be useful in the development of rehabilitation devices for neuromotor deficits.

5 Conclusion

Our study indicates that VAS(M), VAS(L), and RF were highly co-activated, whereas hamstrings had lesser contribution towards walking with such kinematic constraints. In contrast to walking, GR was minimally activated and TA activation was higher and more consistent while walking on the slackline. Overall, the synergy structure altered when walking on a slackline, as muscles with higher contribution during normal walking contributed less during slacklining. In summary, this work suggests that healthy individuals elicited altered synergies as a strategy to simplify motor control when task dynamics were changed.

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