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Temporal structure of variability reveals similar control mechanisms during lateral stepping and forward walking

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Temporal structure of variability reveals similar control mechanisms during lateral stepping and forward walking

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A R T I C L E I N F O

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A B S T R A C T

Previous research exploring a lateral stepping gait utilized amount of variability (i.e. coefficient of variation) in the medial-lateral (ML) and anterior-posterior (AP) direction to propose that the central nervous system's active control over gait in any direction is dependent on the direction of progression. This study sought to further explore this notion through the study of the temporal structure of variability which is reflective of the neuromuscular system's organization of the movement over time. The largest Lyapunov exponent (LyE) of the reconstructed attractors for the foot's movement in the AP and ML was calculated. Results revealed that despite the obvious mechanical differences between a lateral stepping gait and typical forward walking, the central nervous system's organization of the movement of the feet is similar in the primary planes of progression, as well as the secondary planes of progression, despite being different anatomical planes during the locomotive tasks. In addition, consistent with previous studies exploring amount of variability, the secondary plane for both locomotive tasks proved to have larger LyE values than the primary plane of progression ($F_{1,9}$ = 35.086, p < 0.001). This is consistent with less dependency from stride-to-stride in the secondary plane implying increased active control.

1. Introduction

Previous studies that demonstrated increased variability in the medial-lateral (ML) direction compared to the anterior- posterior (AP) direction during walking has led human movement scientists to believe that the ML direction is under greater active control while the AP direction is more influenced by passive mechanisms [1–3]. It is possible that the AP and ML directional control are inherently organized according to fixed anatomical planes [1]. However, it may also be that the amount of active control is an effect of the passive mechanics present during walking.

The role of passive mechanics in upright stabilization during walking cannot be questioned. Kuo [4] demonstrated through a passive walking model the impact of passive mechanics to keep the model from falling over in the AP direction. In experimental work, Donelan et al. [2] utilized elastic bands to add increased ML force at the waist. The result was decreased variability in the ML direction. Their interpretation was that the addition of a stabilizing force increased the amount of passive control in the ML direction which would otherwise require more active control for upright stabilization. Dean et al. [5] extended this work by applying the lateral stabilizing force to the elderly and similarly found a reduced amount of variability. Such results in the elderly are significant as they are speculated to have impaired active control due to aging which results in an increased amount of variability in the ML direction [6].

Recent experimental research investigating a lateral stepping gait suggests that the mechanics of motion act to offload the amount of active control present in any direction during gait [7]. Specifically, subjects performing a lateral stepping gait, where the ML direction is the direction of progression instead of the AP, experienced a reversal of what is found in typical forward walking; the AP direction had a greater amount of variability than the ML. These results persisted in light of the limitation of the novelty of the lateral stepping gait.

Such findings may have strong rehabilitation implications. The amount of variability in the ML direction during typical forward walking has been strongly linked with fall risk and incidence [6, 8, 9]. Thus, step variability in the ML direction has logically been a primary target for decreased fall risk. However, if active control is dependent on the direction of progression and not linked to anatomical planes, then it may be possible to improve the amount of step variability by targeting the plane of motion least benefiting from the mechanics of motion. This would be the ML direction during typical forward walking, but is actually the AP direction during the lateral stepping gait.

However, the results from the Wurdeman et al. [7] study may have been influenced by the usage of a treadmill. A treadmill has a moving belt that provides a constrained area where movement is safely tolerated. The amount of variability in any direction is limited by the physical dimensions. For example, consider during the lateral stepping gait if an imaginary line was present running the length of the treadmill labeled the zero point (Fig. 1). Then in the AP direction (aligned with the width of the treadmill during lateral stepping gait) the constraints of the movement would be one arbitrary unit to each side. One arbitrary unit is equal to half the width of the treadmill belt. Then the maximum possible amount of variability (i.e. standard deviation) after nine steps would be approximately equal to one arbitrary unit. Other measures of the amount of variability such as coefficient of variation would exhibit similar boundary restrictions having certain maximum possible values. However, the potential for variations to the structure of variability is nearly limitless. The structure of variability pertains to the time ordered variance within the movement. So, if the nine steps in our example landed on positions -1, 0, and 1 each of three separate times, the standard deviation would be less than 1 regardless the order that the step positions occurred; however, there are 216 different variations with which the order of those nine steps could occur.

Therefore, the investigation of the temporal structure of variability in the AP and ML directions during typical forward walking and lateral stepping gait could provide additional insights into the active control organization of gait by overcoming the boundaries of the amount of space available during stepping on a treadmill. In particular, if the active control of movement is related to the direction of progression [7], then it could be expected that the temporal structure of variability for the movement pattern that emerges in the primary plane of progression during typical forward walking (i.e. AP) and the primary plane of progression during lateral stepping gait (i.e. ML) would be similar. Further- more, the secondary plane of progression during these modes of locomotion would also be similar. However, as observed in the amount of variability analysis [7], we would expect the temporal structure of variability to be different between the two planes (AP and ML), reflective of different active control strategies. The temporal structure of variability can be analyzed through the largest Lyapunov exponent (LyE). The LyE measures the amount of divergence within the reconstructed state space of a time series [10]. We expect increased LyE values (greater divergence within the movement pattern) for the secondary plane of progression as the active control processes must continuously search for the best movement within the confines of the task.

Table 1
Subject Demographics.

Gender	6 M, 4 F
Age (years)	24.80 ± 4.39
Lateral Stepping Preferred Speed (m/s)	0.344 ± 0.037
Forward Walking Preferred Speed (m/s)	1.104 ± 0.197
Height (cm)	175.32 ± 11.10
Mass (kg)	73.39 ± 17.11

2. Methods

2.1 Subjects

Ten healthy young subjects (Table 1) were recruited to participate. All subjects gave written informed consent in accordance with the Medical Center's Investigational Review Board. All subjects were required to have capacity to provide consent and were currently exercising 2–3 times a week. Subjects were excluded based on inability to provide consent, pregnancy, or presence of any neurological, vestibular, or musculoskeletal conditions that may affect gait.

2.2 Study Protocol

Subjects came to the motion analysis laboratory to perform a lateral stepping gait. Subjects wore their own standard athletic shoes. Retroreflective markers were affixed to the posterior heel and second metatarsophalangeal joint on both subject's feet. Subjects performed a lateral stepping gait on a standard treadmill (Bodyguard Fitness, St. Georges, QC, Canada) at their preferred speed. An eight-camera motion capture system (EvaRT, Motion Analysis Corp., Santa Rosa, CA, USA) sampling at 60 Hz. The sampling frequency was determined a priori through power spectral analysis, which showed 99% of the signal to exist under 6 Hz. Thus, 60 Hz satisfied the minimum determined by Nyquist frequency, and at a magnitude of 10 times the maximum frequency of 6 Hz would be able to capture any spurious movement up to 30 Hz. Subjects faced to their left such that their left leg was in the lag leg position. Subjects were instructed to keep their head up while stepping, to not cross their feet, and at no point to have both feet off the ground (i.e. no aerial phase).

Preferred speed was determined by incrementally increasing the treadmill speed at 0.045 m/s until the individual communicated that the comfortable preferred speed was reached. At that point, the speed was increased another increment to confirm that the speed was at that point too fast. Upon confirmation, the treadmill speed was reduced back to the preferred speed for collection trials. If it was not confirmed that the previous speed was preferred, then the process was repeated and continued until the preferred speed was reached. After selection of preferred speed, subjects were given an initial three minute practice trial. This was followed by a minimum of one minute rest. At this point the subject performed three minutes of continuous lateral stepping gait. Data from each subject's trial was then exported for further analysis. Subjects returned to the laboratory for a forward walking trial within eight weeks. The forward walking trial was performed under the same data collection procedures. Subjects chose a preferred walking speed for forward walking independent of their lateral stepping gait speed.

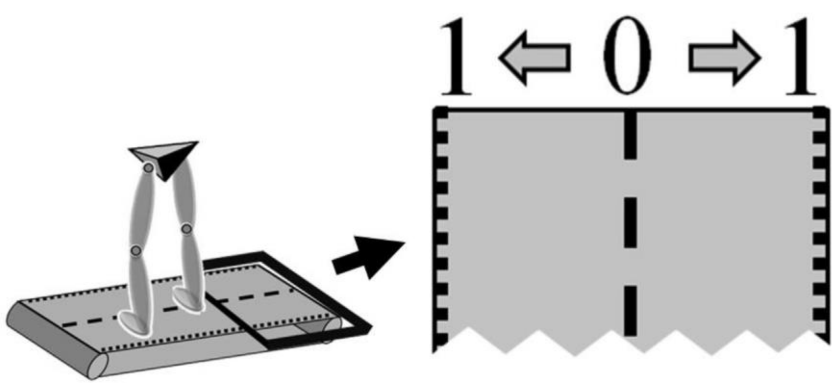

Fig. 1. The physical constraints of the treadmill may be limiting the amount of variability. If the middle of the belt were the ''0'' point, and then either direction to the side was a maximum of 1 arbitrary unit, then the maximum standard deviation in that direction could only be approximately 1 arbitrary unit. However, the temporal structure of variability has nearly limitless variations that the order of steps could occur.

2.3 Data Analysis

Foot position was calculated as the midpoint between the heel and toe marker on each foot. The movement trajectory of the feet was not filtered. This was done as filtering the signal for a nonlinear analysis can distort the reconstructed attractor [11]. The lateral stepping gait orients individuals such that there is a leading leg and a lagging leg. Contrary to typical forward walking where the legs are constantly alternating position, the lateral stepping gait does not permit this. As a result, the data from the two legs was not combined for the lateral stepping gait. Furthermore, for appropriate statistical analysis, the foot position data were kept separate for forward walking as well. From the foot position data, the X and Y coordinate time series were analyzed. For the typical forward walking, the X direction corresponds to the anatomical ML direction. For the lateral stepping gait, the X direction corresponds to the anatomical AP direction.

The X and Y coordinate time series for both feet during each walking condition were embedded with their proper time lag into the reconstructed state space [11, 12]. From the properly reconstructed state space attractors, the LyE was calculated [10]. The calculation of LyE explained in greater detail elsewhere [10, 11] but is briefly explained here. First, the recorded time series (in this case the calculated midpoint position of the heel and toe markers in the X and Y directions) is properly embedded into its state space. The result is the original time series vector x(t) is translated into the matrix representation of the state space:

$$y(t) = [x(t), x(t+\tau), \ldots, x(t+(M-1)\tau)].$$

This is done through the use of an embedding dimension (M) dictating the number of time delay copies, and the time lag (t) dictating the number of points advanced (i.e. delayed) before the start of each subsequent vector delay within *y*(*t*). The embedding dimension is calculated using the false nearest neighbors algorithm [11] while time lag is calculated using average mutual information algorithm [11]. The result of proper state space reconstruction is the behavioral attractor, where portions of the attractor represent similar instances within the movement. In this manner, a behavior that is perfectly periodic and repeating exactly with each cycle such as a sine wave (Fig. 2A) would be reflected through an attractor with each trajectory lying perfectly over the previous and any instance of the cyclical movement is therefore seen to be exactly the same as the previous and exactly the same as the next. On the other hand, if an entirely random system is considered (Fig. 2B), then the attractor presents a visible ‘‘cloud’’, where any instance of occurrence may not have ever occurred previously, and there can be no certainty that such an instance will ever occur again. Finally, there is stronger possibility of a system that occurs somewhere between these systems (Fig. 2C). In this case, a general pattern of trajectories is identified and any instance of occurrence within the attractor can predict a ‘‘similar’’ instance in the future or the past, with the ‘‘similarity’’ of the instance being dictated by the divergence of trajectories in the attractor. The LyE quantifies this divergence in the movement trajectories of the reconstructed attractor.

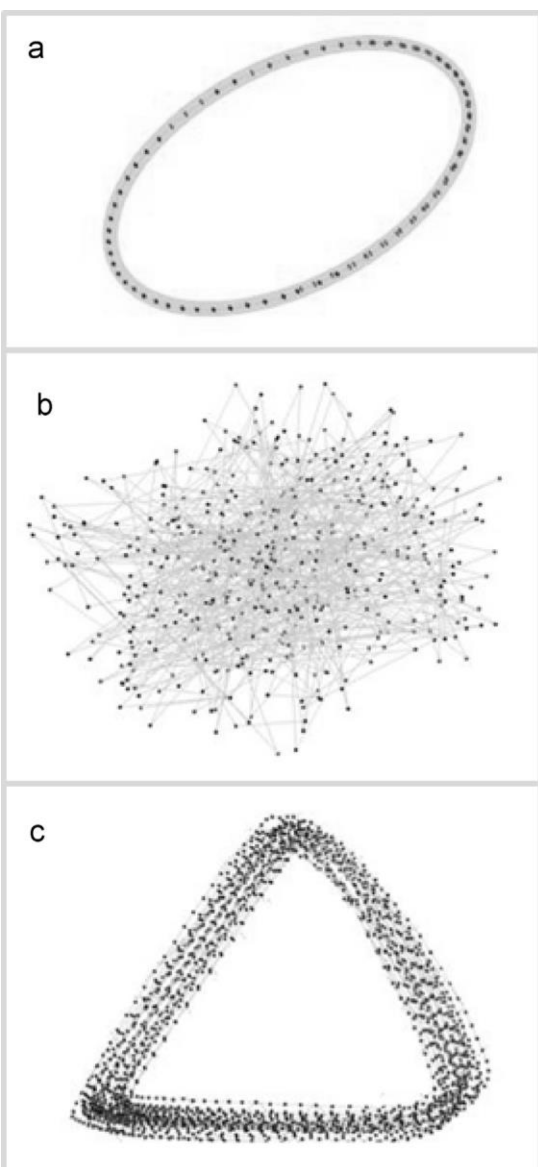

Fig. 2. The reconstructed attractor for a perfectly repeating signal such as a sine wave (A), will reflect a behavior with no divergence within the attractor. An entirely random signal such as white noise (B) will have an attractor with no apparent structure. As a result, any incidence of a particular point provides no predictability on future occurrences of the incident reflecting the truly random nature of the signal. A biological signal (C) will have an attractor that shows a somewhat cyclical behavior, where any incidence of a point in the movement allows for an approximation of future points being similar by having close approximation within the attractor.

The calculation of the LyE is then performed by moving through the reconstructed state space matrix $y(t)$. A nearby neighboring point to an initial reference point in $y(t)$ is selected meeting the criteria of being within a minimum angle to the orthogonal of the trajectory (0.3 radians[10] greater than a minimum scale length (0.0001)[10], and less than a maximum scale length (0.1 times the maximum diameter of the attractor)[10]. The Euclidean distance between the neighboring point and the reference point is calculated as (*dt*). The two points are then allowed to propagate through their respective trajectories for a predefined distance (n = 3), at which time the distance between the points is recalculated as (*dt'*). The local expansion/contraction rate is then calculated as:

$$Z = \log_2(dt'/dt)$$

Z is then normalized to the time that the points were allowed to propagate through their trajectories (n/Fs) where Fs is the sampling frequency. Subsequently, the longtime average of the running sum of the Z values is calculated. At this point the neighbor is replaced with a new nearest neighbor and the process is repeated. Once the entire state space matrix $y(t)$ has been propagated, the longtime average of Z is defined to be the LyE [10].

Since the LyE examines variance from cycle-to-cycle, appropriate comparison between time series should examine a similar number of cycles. Therefore, each time series was cropped to 104 orbits which was the minimum number of strides present among all subjects for both conditions. A three way repeated measures analysis of variance (2 x 2 x 2) was implemented to test for differences in the LyE group mean values for condition (forward walking versus lateral stepping), leg (left versus right), and direction (X versus Y). The level of significance was set at 0.05.

3. Results

There was no significant main effect for condition (forward walking versus lateral stepping: $F_{1,9}$ = 0.727, p = 0.416; Fig. 3) or leg (left versus right: $F_{1,9}$ = 3.470, p = 0.095). Only the direction was significantly different. The X had significantly greater LyE values compared to the Y direction (X versus Y: $F_{1,9}$ = 35.086, p < 0.001). As mentioned above, X represents the direction orthogonal to the direction of progression which equates to the ML direction during typical forward walking and the AP direction during lateral stepping gait. There were no significant interactions (condition*- leg: $F_{1,9}$ = 0.816, p = 0.390; condition*direction: $F_{1,9}$ = 3.166, p = 0.109; leg*direction: $F_{1,9}$ = 0.043, p = 0.840; condition*leg*direction: $F_{1,9}$ = 0.002, p = 0.965).

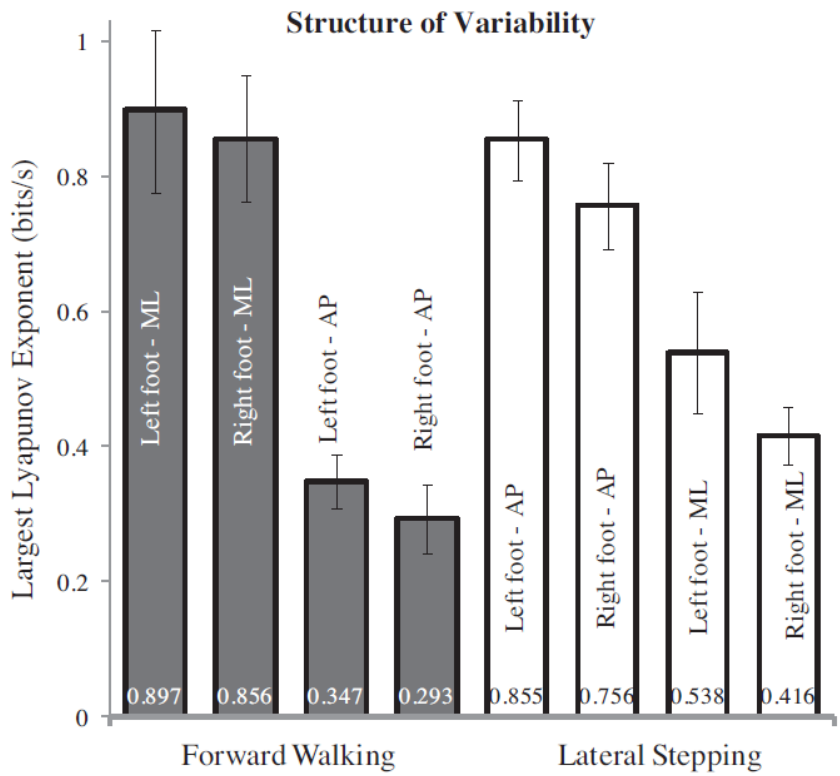

Fig. 3. The largest Lyapunov exponent for both the right and left foot during the different modes of locomotion (forward walking and lateral stepping gait). Only the comparison of the primary plane of progression to the secondary plane of progression was significantly different. Note the primary plane of progression corresponds to the AP direction in typical forward walking and the ML direction in the lateral stepping gait. There were no significant differences between the forward walking and the lateral stepping gait or between left and right feet. (AP, anterior- posterior; ML, medial-lateral; the exact group mean values are also listed within the bars.)

4. Discussion

Our results supported our hypotheses. The secondary plane of progression had significantly greater attractor divergence (i.e. larger LyE values) than the primary plane of progression. Interestingly, there were no differences in the different planes between lateral stepping gait and typical forward walking. Although the direction of progression in the lateral stepping gait is aligned with the ML but aligned with the AP for typical forward walking, the divergence of the attractors was not different between these directions between conditions (Fig. 4). The same was true for the secondary plane of progression (AP for lateral stepping gait and ML for forward walking).

In terms of locomotion, greater LyE values in the secondary plane are consistent with previous research that has proposed active control is dependent on the direction of progression [7]. Specifically, foot placement in the secondary plane serves to establish balance, catching the body's center of mass as it deviates from the desired path. Thus, decreased dependency of foot placement from stride-to-stride in the secondary plane would be highly beneficial. Such a strategy would permit adaptability, allowing the foot to be placed at the best position with each step to achieve greatest walking balance. This sort of quick adaptability, however, would necessarily require a more active control process from the central nervous system. This notion is consistent with previous findings comparing the amount of variability in the primary and secondary planes of progression during typical forward walking [1, 5] and lateral stepping gait [7]. In these studies, the secondary plane of progression, whether during a lateral stepping gait or typical forward walking, was found to have greater amount of variability.

The surprising finding in this study may not be the increased LyE values for lateral stepping gait in the secondary plane, but rather the similarity between the typical forward walking and the lateral stepping gait. While clearly the mechanics behind these two different tasks are different, the organization of the neuromuscular system to control foot placement and maintain upright balance appears to be similar (Fig. 4). However, the view that these findings are only the result of the mechanical processes in each direction, and thereby not reflective of the neuromuscular system's control, should be considered. A strong limitation to this study is still the drive of the treadmill belt. It is possible that the motion of the legs in the direction of progression is being consumed by the drive of the belt, where the dominant task in this direction is simply to lift and swing the leg in the direction of progression, then wait while the treadmill pulls the leg backwards. The secondary plane of progression, however, receives no aid from the treadmill belt drive. Thus increased variability in the secondary plane of progression, both in terms of amount of variability, [7] as well as the current results examining the structure of variability, may be an artifact of the treadmill belt drive. Therefore, our results should be interpreted cautiously and need to be verified with an overground protocol.

If we are to assume these results reflect motor control processes, then they may have strong rehabilitation implications. Specifically, step width variability during typical forward walking (i.e. increased amount of variability in the secondary plane of progression) has been strongly linked to increased fall risk and incidence in the elderly [6, 8, 9] as well as a strong discriminator between young and elderly gait[14]. Based upon the evidence from this study and previous work [7], it may be possible that any intervention aimed at improving step width variability during typical forward walking to potentially reduce fall risk may only need to target the secondary plane of progression. In particular, an intervention incorporating the lateral stepping gait may effectively improve the neuromuscular system's ability to control foot placement in the secondary plane of progression, thereby increasing walking balance. We believe that improving the neuromuscular system's overall ability to control balance in a dynamic task would benefit balance control during other tasks such as turning and maneuvering obstacles. This, however, would also need to be tested in a controlled setting.

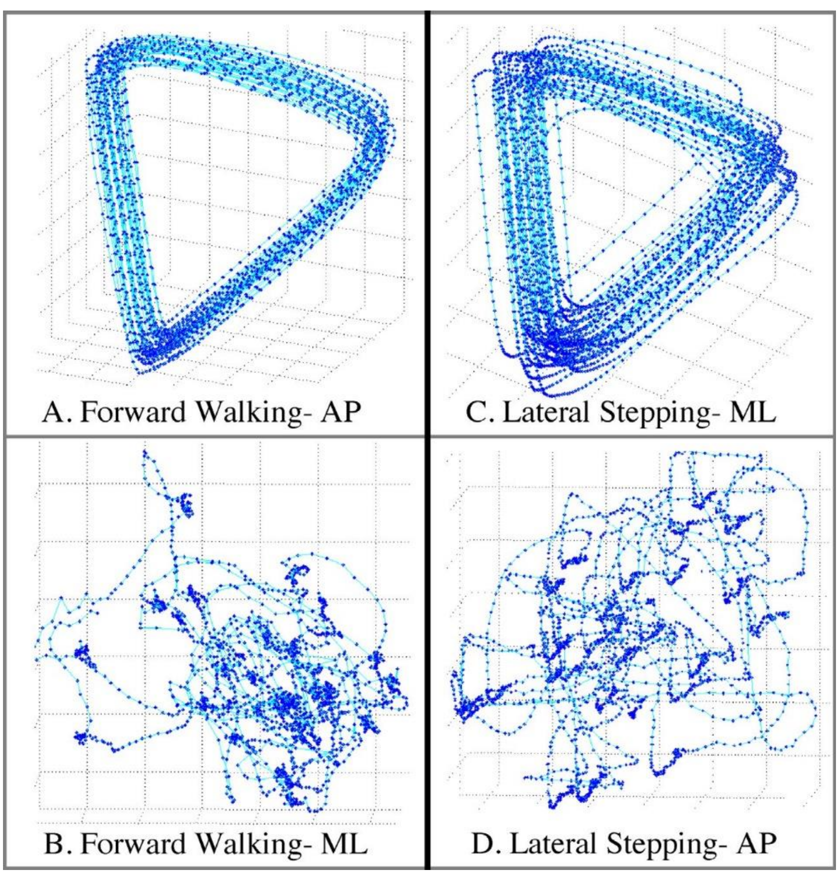

Fig. 4. Example three dimensional reconstructed state space attractors for the left foot of one subject. The attractor for the movement of the foot in the primary plane of progression during forward walking (A) is similar to the primary plane of progression during lateral stepping (C). The same is seen for the secondary plane of progression during forward walking (B) and lateral stepping (D). The calculation of the largest Lyapunov exponent confirms similar attractor divergence for the tasks in these directions. It should be noted however, the primary plane of progression during lateral stepping is the medial-lateral whereas in forward walking it is the anterior-posterior.

In addition, there are certain limitations to this study. First, repeatability of the treadmill trials was not assessed as subjects only performed single trials in each the lateral stepping and forward walking directions. Second, the order of conditions was not randomized, thus there may have been certain effects due to order. This was done to assure that the more difficult walking task (lateral stepping) was completed prior to routine forward walking. Thus, in the event that any subject did not desire or was unable to do the lateral stepping, it would not be necessary to recall the individual for the second collection day. We do feel that the 8 week washout period between trials helped to reduce this effect, but cannot totally disregard it. Furthermore, the subjects performed the lateral stepping task in a left foot lagging position. While all subjects reported themselves to be right foot dominant, it is possible that location of the dominant foot would influence the results. This, however, was not the case in a previous study examining the amount of variability during a lateral stepping task where subjects performed the lateral stepping in both directions [7]. We also did not analyze gender differences due to lack of grounds for such analysis. It is possible, however, that anatomical differences in the pelvis geometry may lead to changes in foot placement especially in a lateral stepping task where large emphasis is placed on hip abduction/adduction motion. Further work will need to expand on these results to test such differences. Finally, our study had a limited sample size, thus must be interpreted cautiously. However, the consistency of these results in terms of the structure of variability with previous work examining amount of variability in a larger sample population [7], would seem to reinforce the results found in this limited sample size.

5. Conclusion

In conclusion, this study combined with evidence from previous work examining a lateral stepping gait strongly supports the notion that the central nervous system's control over gait is highly affected by the mechanics of motion. The central nervous system seems to take a less active role over the control of movement in the primary plane of progression. This is in contrast to the secondary plane of progression where the control of the foot movement is more actively adjusted to permit greatest walking balance. Furthermore, despite the very different movements between lateral stepping gait and typical forward walking, the stride-to- stride fluctuations that are present in the motion of the foot are similar in the primary as well as the secondary planes of progression. Thus, while the mechanics are different between lateral stepping gait and typical forward walking, the central nervous system seems to temporally organize movement control similarly for these locomotive tasks.

Conflict of interest

The authors have no conflict of interest in this research.

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