

ORIGINAL ARTICLE

Comparison of erector spinae muscle activity and center of body mass variability between forward and backward walking

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Abstract

Backward walking is often used in rehabilitation to improve balance, although it differs biomechanically from forward walking. This study investigated the variability of the center of mass movement and the intensity of erector spinae muscle activity during backward walking and forward walking. The analysis included intra-participant variability (one participant performed 10 trials each of forward walking and backward walking) and inter-participant variability (eight participants each performed one trial of forward walking and backward walking). The results showed that center of mass was positioned higher and exhibited greater variability during backward walking, particularly in the single support phase. In contrast, erector spine muscle activity did not consistently increase during backward walking, and the timing of muscle activation differed between backward walking and forward walking. While backward walking requires unique postural control strategies and dynamic balance adjustments, it does not therefore necessarily lead to increased erector spine muscle activation.

INTRODUCTION

Backward walking (BW) is important in rehabilitation and exercise therapy (Balasukumaran, 2019), and is frequently used in protocols to improve balance and to strengthen leg muscles. Benefits of BW have been shown for conditions such as ankle instability, chronic low back pain, Parkinson disease, post-stroke rehabilitation, and knee osteoarthritis. Reported improvements as a result of BW include improvements in balance, gait stability, and lower limb function (Balasukumaran, 2020; Ansari, 2018; Hackney, 2009; Grobbelaar, 2017; Moon, 2019; Rose, 2018; Wu, 2020). BW has a movement pattern that is distinct from forward walking (FW). It is hypothesized that there is increase in the activity level of the trunk and lower limb muscles, and greater demand on postural control mechanisms. This hypothesis is supported by studies (Singh, 2020), which suggest that muscle activity and variability tend to increase when walking in environments with greater balance challenges. Increase in lower limb muscle activity has been shown during BW, but there are insufficient investigations into the activity of the erector spinae muscles (ESM), which are critical for postural control (Ansari, 2018). The detailed biomechanical dynamics during BW are not yet fully understood.

The ESM play a fundamental role in maintaining trunk stability. During walking, the center of body mass (CoM) shifts antero-posteriorly, laterally, and vertically in coordination with the movement of the limbs, necessitating active engagement of the ESM to preserve balance. Visual feedback is restricted during BW, so maintaining balance perhaps becomes more challenging, leading to increased ESM activation and potentially more variable muscle activity patterns. Furthermore, walking modalities deviating from standard FW, such as BW or walking on uneven or inclined surfaces, may lead to greater variability in vertical CoM motion and increased lower limb muscle activity (Akhil, 2022). Non-conventional gait patterns may therefore impose additional demands on postural control and muscle coordination, highlighting the need for further investigation into the stability challenges posed by BW. Nonetheless, detailed analyses supporting these observations are scarce, and the specific activity patterns and variability of the ESM during such tasks require further investigation.

The movement of the CoM is a critical parameter for assessing gait stability and efficiency. CoM movement during BW may be less stable than in FW, potentially influencing ESM activity. Greater understanding of the relationship between CoM variability and ESM activity is thought to be essential for developing

effective rehabilitation and training methods aimed at enhancing balance and strengthening trunk muscles.

The author hypothesizes that during BW, both CoM motion and ESM activity will show greater intensity and variability compared with during FW. However, there may be differences in how this variability is distributed across different phases of the gait cycle.

This study therefore compares CoM movement and the variability of ESM activity patterns during FW and BW, in order to elucidate the unique characteristics of each walking modality. The ultimate goal is to contribute to the refinement of rehabilitation strategies and the development of more effective trunk muscle training protocols.

METHODS

Participants and experimental design

The present study was designed to evaluate the variability of CoM movement and ESM activity under both intra-participant and inter-participant conditions. Evaluating both conditions should provide a more comprehensive understanding of BW. The intra-participant condition assesses how an individual's performance varies across trials, while the inter-participant condition examines variability across different individuals performing the same task. This dual approach allows for the capture of both individual-specific patterns and general trends across participants.

Participants were healthy adult volunteers recruited at Osaka Kawasaki Rehabilitation University. A total of nine participants were included in the study, as detailed in Table 1. To assess intra-participant variability, a single participant completed ten trials each of FW and BW. To assess inter-participant variability, eight participants were each evaluated during one trial of FW and one trial of BW. Participants were randomly selected without controlling for body type or sex, resulting in natural variability within the group. They were instructed to walk at their self-selected normal gait speed on the laboratory floor, defined as the pace at which they naturally felt most comfortable during everyday walking.

All participants were accustomed to walking in daily life, and it was confirmed that none of the participants had specialized training or skills in BW. This criterion was adopted to evaluate the variability in ESM activity and CoM movement in a general adult population.

The walking motion was segmented into a single gait cycle, defined as the period from the time the left foot left the ground until it left the ground again. Each gait cycle was further divided into four phases based on Den Otter et al. (2007): the swing phase, the first double support phase (DS1), the single support phase, and the second double support phase (DS2). The time for each phase was normalized to enable comparisons across trials.

Table 1. The basic physical information of the study participants, including height, weight, body mass index, age and sex

ID	Height (cm)	Weight (kg)	BMI	Age (Years)	Sex
Intra-participant					
1	171	65	22.2	21	Male
Inter-participant					
1	170	68	23.5	21	Male
2	169	66	23.1	21	Male
3	165	53	19.5	21	Female
4	177	72	23.0	21	Male
5	146	36	16.9	21	Female
6	164	62	23.1	21	Female
7	157	55	22.3	21	Female
8	157	53	21.5	21	Female

The study was approved by Osaka Kawasaki Rehabilitation University Ethics Review Board (OK-RU30-A027) and conducted in accordance with the Declaration of Helsinki. Prior to the experiment, participants were provided with a detailed explanation of the study objectives and methods, and written informed consent was obtained. Strict measures were taken to protect participants' privacy; all collected data were anonymized, and steps were taken to ensure that no personal information could be identified during data analysis.

Measurement

Estimation of CoM

In this study, the movement of the CoM during walking was measured in three dimensions. Anatomical landmarks were identified, and markers were attached to key points on the participants' bodies, including the top of the head, the seventh cervical vertebra, the tenth thoracic vertebra, the sternum, the shoulders, the elbows, the wrists, the anterior superior iliac spines, the sacrum, the greater trochanters, the knees, the ankles, and the toes. These specific marker locations were selected to estimate the CoM based on the method described by Winter (2009). Marker position data were collected using a three-dimensional motion capture system (MAC3D System, Motion Analysis, CA, USA). The movement of the markers during FW and BW trials was tracked, and based on these data, the vertical motion of the CoM was calculated from the data. The CoM vertical position was expressed as a percentage of each participant's height. Additionally, to assess the variability in vertical CoM motion, the robust coefficient of variation based on the median absolute deviation (RCV_M), a measure of data dispersion that does not rely on the assumption of normal distribution, was calculated previously reported (Arachchige, 2022).

Processing of electromyography data

To assess ESM activity, surface electromyography (P-EMG plus, Oisaka Electronic Equipment, Hiroshima, Japan) electrodes were attached to the left lumbar ESM of each participant. Electromyography data were initially filtered using a band-pass filter (20–400 Hz), followed by full-wave rectification, and then smoothed using a low-pass filter with a cutoff frequency of 6 Hz to reduce noise in the electromyography signal. Furthermore, muscle activity data from each trial were normalized to the maximum muscle activity observed during the FW trial, expressed as

a percentage of the maximum value (%max). For intra-participant comparisons, the maximum value across all FW trials was set at 100%, while for inter-participant comparisons, the maximum value from each participant's FW trials was set at 100%. This normalization facilitated consistent evaluation of muscle activity across trials. In the electromyography analysis, muscle activity patterns and levels were examined during each phase of the gait cycle. To assess variability in muscle activity, the RCV_M of muscle activity was calculated for each trial.

Statistical analysis

The activity patterns of the ESM and the vertical displacement of the CoM were recorded for each trial, and the consistency and variability of the data were analyzed. Detailed comparisons were made to examine how FW and BW patterns differed for each participant. Specifically, differences in ESM activity and CoM movement were statistically analyzed by comparing the activity levels and patterns of CoM movement and ESM activity between FW and BW. To assess the variability in CoM movement and muscle activity, RCV_M was calculated, but comparisons between FW and BW were conducted qualitatively due to the limitations in statistical comparability of RCV_M values.

Intra-individual variability was evaluated by comparing the magnitude and variability of each participant's trial data, while inter-individual variability was assessed by comparing the variability across participants. The Wilcoxon rank-sum test (Mann-Whitney U test) was used for intra-participant comparisons between FW and BW, and the Wilcoxon signed-rank test was used for inter-participant comparisons. Specifically, statistical tests were applied to the spatiotemporal gait parameters, as well as the median values of the CoM vertical position and ESM activity for each phase of the gait cycle (intra-participant comparisons were made across trials, and inter-participant comparisons were made across participants). A significance level of 5% was used to determine statistical differences between FW and BW. Preprocessing of the data, electromyography filtering, and statistical analyses were conducted using the open-source statistical software R, version 4.4.0.

RESULTS

In this study, the variability of CoM and ESM activity were compared during FW and BW.

Gait parameters

First, the spatiotemporal parameters of walking were analyzed (see Table 2). In both the intra-participant and inter-participant conditions, gait speed showed a trend toward being slower in BW than in FW, although the difference was not statistically significant. For cadence and duty cycle, no differences were observed between FW and BW.

CoM vertical displacements

The results of the vertical movement of the CoM are presented in Figures 1, 2A and 2B. Figure 1 compares the median CoM vertical position between the gait conditions (FW and BW) across different phases. Figure 2A illustrates the time-series data of CoM vertical position during each phase, while Figure 2B depicts the time-series data of RCV_M values, representing the variability of CoM vertical movement.

Comparison of median CoM vertical position between FW and BW reveals a general tendency for the CoM position to be higher during BW in both the intra-participant and inter-participant conditions (Figure 1). This difference is particularly evident during the single support and DS2 phases in the intra-participant condition, where statistically significant differences are observed ($p < 0.05$). Although the differences are less pronounced in the inter-participant condition, a

similar trend is still present, especially during the single support and DS2 phases.

The time-series changes in CoM vertical position throughout each gait phase are shown in Figure 2A. The intra-participant condition shows a consistent pattern: the CoM height is higher during BW than during FW. In the inter-participant condition, the overall trend is similar, with BW showing a tendency for a higher CoM height, but the variability between participants results is less consistent in these differences.

Time-series data of RCV_M values is shown in Figure 2B, indicating the variability of CoM vertical movement. In the intra-participant condition, RCV_M is generally higher during BW than in FW in all phases, where BW exhibits a marked increase in variability compared with FW. For the inter-participant condition, RCV_M tends to be higher during BW in the swing phase and single support but is less consistent with variability. This suggests greater inter-individual variability, leading to less pronounced differences between gait conditions. Overall, the RCV_M values remain small, indicating limited variability in the vertical movement of the CoM in both conditions.

In summary, the analysis reveals that while the CoM position tends to be higher during BW than in FW, especially in certain gait phases, the degree of difference varies between the intra-participant and

Table 2. Gait parameters for FW and BW

Intra-participant	FW N = 10 ¹	BW N = 10 ¹	p-value ²
Speed (m/s)	0.99 (0.85, 1.03)	0.81 (0.79, 0.88)	0.064
Cadence (steps/min)	108.7 (101.4, 115.2)	100.3 (99.3, 106.7)	0.2
Duty Cycle (%)	61.6 (60.8, 63.4)	59.6 (55.3, 62.8)	0.2
¹ Median (Q1, Q3)			
² Wilcoxon rank sum test			
Inter-participant	FW N = 8 ¹	BW N = 8 ¹	p-value ²
Speed (m/s)	0.94 (0.89, 1.15)	0.87 (0.72, 0.97)	0.078
Cadence (steps/min)	109 (107, 112)	115 (96, 117)	>0.9
Duty Cycle (%)	59.3 (58.1, 61.2)	62.1 (57.9, 63.8)	0.3
¹ Median (Q1, Q3)			
² Wilcoxon signed rank sum test			

In both the intra-participant and inter-participant conditions, there was no significant difference in gait speed, but BW tends to be slower. In contrast, the cadence and duty cycle did not differ between FW and BW across both conditions.

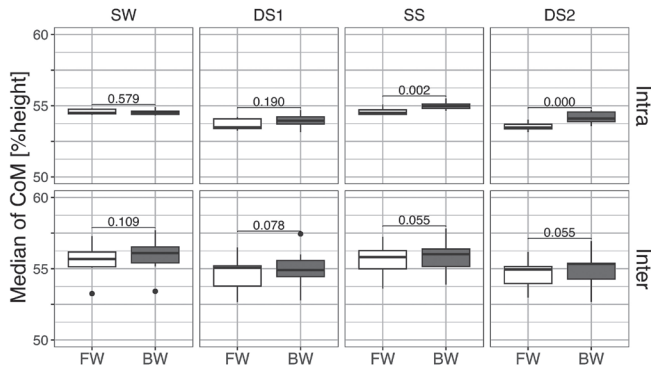


Figure 1. Comparison of the median CoM vertical position between FW (white box) and BW (gray box) across different gait phases (SW, DS1, SS, DS2)

Data are shown separately for the intra-participant and inter-participant conditions. p -values from the Wilcoxon rank-sum test (Mann-Whitney test) are displayed for the intra-participant condition, while p -values from the Wilcoxon signed-rank test are displayed for the inter-participant condition. SW: swing phase; DS1: first double stance phase; SS: single stance phase; DS2: second double stance phase.

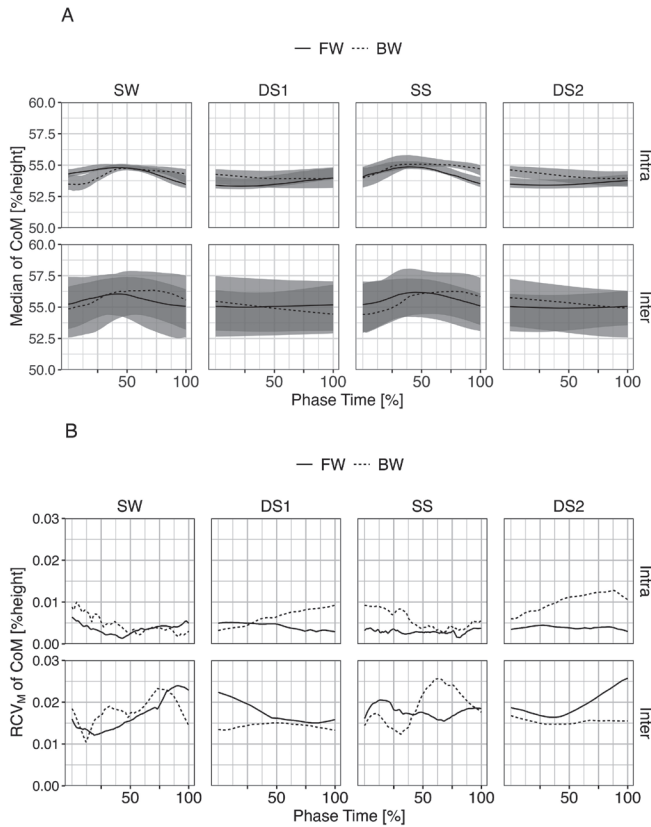


Figure 2. CoM vertical displacements

The gait cycle is divided into four phases, each time-normalized to 100%. The horizontal axis in all figures represents the duration of each phase of the gait cycle as a percentage. The upper graphs show intra-participant CoM vertical displacement, while the lower graphs show inter-participant CoM vertical displacement. In Figure 2A, the vertical axis represents the vertical displacement of CoM as a percentage of height. Solid lines indicate FW, and dashed lines indicate BW, with each curve representing the median of the entire dataset. The shaded gray area indicates the interquartile range. In Figure 2B, the vertical axis (RCV_M) represents the variability in CoM vertical displacement across trials. Solid and dashed lines represent FW and BW, respectively, with higher values indicating greater variability in CoM vertical movement during each phase. SW: swing phase; DS1: first double stance phase; SS: single stance phase; DS2: second double stance phase.

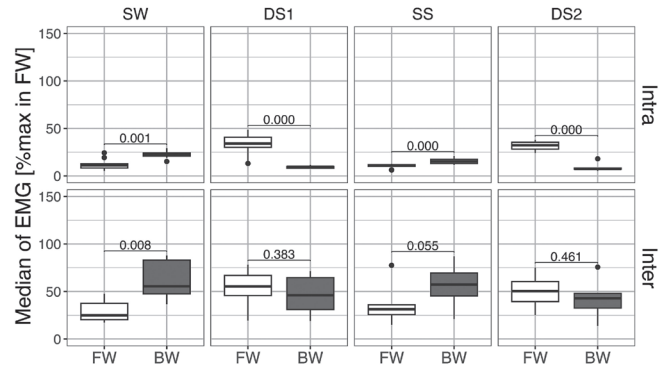


Figure 3. Comparison of median ESM activity between forward walking (FW; white box) and backward walking (BW; gray box) across different gait phases (SW, DS1, SS, DS2)

The boxplots display the median and interquartile ranges, with whiskers representing the range of values excluding outliers. p -values for intra-participant comparisons between FW and BW are directly indicated on the figure. SW: swing phase; DS1: first double stance phase; SS: single stance phase; DS2: second double stance phase.

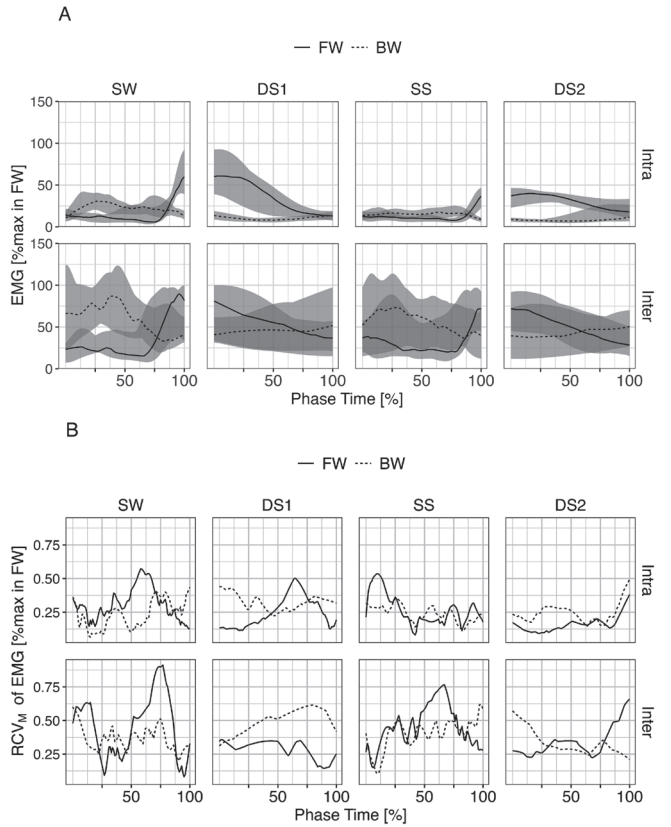


Figure 4. ESM activities

The shaded gray area indicates the interquartile range. (B) Time-series plots of the RCV_M values, representing the variability of ESM activity during each gait phase for FW (solid line) and BW (dashed line). Data are shown separately for the intra-participant (top) and inter-participant (bottom) conditions. SW: swing phase; DS1: first double stance phase; SS: single stance phase; DS2: second double stance phase.

inter-participant conditions. Additionally, although the variability of CoM movement indicated by RCV_M is higher during BW in some phases, it remains generally low, reflecting a limited range of variation in the vertical movement of the CoM.

ESM activity

The results of ESM activity are presented in Figures 3, 4A, and 4B. Comparison of median ESM activity between FW and BW for each gait phase is shown in Figure 3. The time-series data of median ESM activity throughout each gait phase is shown in Figure 4A, while the time-series data of the RCV_M values are shown in Figure 4B, representing the variability of ESM activity.

The median ESM activity between FW (white box) and BW (gray box) across different gait phases are compared in Figure 3. In the intra-participant condition, BW shows significantly higher median muscle activity than FW during the swing phase and the single support phase, as indicated by p -values. Conversely, FW shows higher muscle activity during DS1 and DS2. In the inter-participant condition, significant differences were found only in the swing phase ($p = 0.008$), with BW displaying higher muscle activity. Although no statistically significant differences were observed in the other phases ($p > 0.05$), the overall trends were similar to those seen in the intra-participant condition. Specifically, muscle activity tended to be higher during BW in the swing phase and single support phases, while FW showed higher activity during DS1 and DS2.

Time-series data of the median ESM activity for each gait phase are shown in Figure 4A, with solid lines representing FW and dashed lines representing BW. In the intra-participant condition, BW generally shows lower ESM activity levels than FW. However, this trend is less apparent in the inter-participant condition, where the differences in muscle activity between FW and BW vary more across the different phases. Although the overall muscle activity levels differ depending on the phase, there is a shift in activation patterns between FW and BW. Specifically, in FW, muscle activity tends to be higher during DS1 and DS2, while in BW, the activity is elevated during the single support phase.

Time-series data of the RCV_M values are shown in Figure 4B, indicating the variability in ESM activity throughout each phase of the gait cycle. Overall, the differences in RCV_M between FW and BW are not clearly distinguishable across all phases. In BW, the differences in variability between gait phases are

less pronounced, indicating a more uniform pattern of ESM activation across phases. However, in both intra-participant and inter-participant comparisons, RCV_M tended to be higher during FW, particularly during the swing phase and single support phase, where BW shows a lower variability.

The overall trends observed for CoM variability and ESM activity were similar between the intra-participant and inter-participant conditions. Both conditions showed increased CoM variability during BW, particularly in the single support phase, and differences in ESM activity across gait phases. Although direct statistical comparisons between intra- and inter-participant variance were not conducted due to differences in data structure, the consistency in trends suggests a similar pattern of adaptation in both conditions.

DISCUSSION

This study aimed to investigate the differences in CoM movement and ESM activity during FW and BW. The results revealed distinct characteristics in both CoM displacement and ESM activation between the two gait patterns, providing insight into the unique challenges posed by BW in terms of postural control and muscle coordination.

CoM displacement and postural control

The results of this study revealed some differences in the vertical displacement of the CoM between FW and BW, suggesting different demands on postural control between these gait patterns. The median CoM height tended to be higher during BW in both the intra-participant and inter-participant conditions (Figures 1 and 2A). This elevation was particularly evident during the single support and DS2 phases in the intra-participant condition. These differences in single support and DS2 are possibly influenced by asymmetries in foot function (Wang, 2012), although foot dominance was not tested in this study. In addition, the higher CoM height during BW may be due to a reduced ability to utilize the pendulum-like mechanism of walking compared with FW. Given the limited number of participants and trials, however, these findings should be interpreted with caution.

The variability of CoM movement, as measured by RCV_M , was generally higher during BW, particularly in the intra-participant condition (Figure 2B). This increased variability suggests that maintaining a consistent CoM trajectory might be more difficult during BW, possibly due to the absence of forward momentum and reduced visual feedback compared with FW.

However, even during BW, the overall RCV_M values remained relatively low, indicating that despite these challenges participants could maintain CoM movement within a controlled range. This observation is consistent with the results of previous studies that suggested that the body may employ compensatory strategies to minimize CoM movement variability during gait tasks with increased demands (Chong, 2009).

In the inter-participant condition, however, the trend of higher CoM variability during BW was less consistent. This could be due to individual differences in balance management strategies during BW, possibly influenced by variations in physical fitness, balance ability, and prior experience with backward walking. Although these factors were not directly measured in this study, the variability observed between participants suggests that BW adaptation may differ between individuals.

Despite the observed tendency for a higher CoM height and greater variability during BW, the overall range of vertical CoM displacement remained limited. This suggests that while BW may pose distinct challenges to postural control, participants may have therefore adapted their gait patterns to maintain stability within a certain threshold. This adaptation might reflect an effort to optimize energy expenditure while maintaining balance, even under the altered dynamics of BW. Without direct measurements of energy expenditure or muscle coordination, interpretations regarding these adaptations should remain tentative.

In summary, BW is suggested to be involved in different CoM movement patterns and variability in maintaining CoM stability to FW. These differences may reflect the unique postural demands of BW, including the challenges of balance control without forward momentum and visual input. Given the limited sample size and the use of single trials for inter-participant comparisons, caution is needed when generalizing these findings, and further studies with larger sample sizes and repeated trials are needed to confirm these observations.

ESM activity and variability

ESM activity patterns differed between FW and BW. Specifically, FW showed increased ESM activity during DS1 and DS2, while BW showed increased activity during the swing phase and the single support phase. In FW, the ESM are particularly active during the during DS1 and DS2, because this period requires the trunk to stabilize against the impact forces generated when both feet are in contact with the ground. This movement helps to absorb and manage

the mechanical loads associated with foot contact, contributing to overall stability as the CoM moves forward. In contrast, BW places greater demands on the ESM during the more unstable single support phases, when the body is supported by only one leg. The backward motion and reduced sensory input from vision increase the challenge of maintaining trunk stability during these phases, making the role of the ESM crucial for postural control. These results also highlighted a phase shift in muscle activation patterns between FW and BW, suggesting different timing of muscle engagement. This observation is consistent with findings of a previous report (Jansen, 2012), that reported lower limb muscle activation patterns reverse between FW and BW. A similar reversal may occur in trunk muscles such as the ESM, reflecting an adaptive strategy to meet the different postural demands of BW, especially when the body is most vulnerable to balance disturbances.

Contrary to initial expectations, ESM activity was not consistently higher in BW than in FW, despite the expected increased postural demands. This suggests that the expected increase in muscle activation due to the instability of BW did not fully manifest. One explanation may be that lower limb muscles, such as the rectus femoris and the tibialis anterior play a greater role in maintaining stability during BW (Asri, 2018). This could allow for a more distributed pattern of muscle engagement, reducing the reliance on the ESM. Additionally, the trunk may rely more on passive stabilizing mechanisms, such as ligamentous support, to maintain stability during BW. However, these interpretations should be considered with caution, as this study did not directly measure coordination with other muscle groups or passive stabilization mechanisms. Further research that includes comprehensive muscle activity analysis is needed to clarify these compensatory strategies.

The variability in ESM activity, as measured by the RCV_M , also yielded unexpected results. Contrary to initial expectations, RCV_M was not consistently higher during BW than in FW. In FW, variability was larger during the single support phases, where muscle activity was relatively low, possibly reflecting greater fluctuations when lower levels of activation are required. In contrast, during phases requiring higher muscle output, such as during DS1 and DS2, ESM activity was more stable, indicating more efficient neuromuscular control when maintaining balance is critical.

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initial expectations, RCV_M was not consistently higher during BW than during FW. In FW, variability was larger during the single support phases, where muscle activity was relatively low, possibly reflecting greater variability when lower levels of activation are required. In contrast, ESM activity was more stable during phases requiring higher muscle output, such as during DS1 and DS2, suggesting that more efficient neuromuscular control when maintaining balance is critical.

The findings that BW did not necessarily result in higher ESM activity or variability have practical implications for rehabilitation and exercise programs. BW might not inherently increase ESM activation as hypothesized, but instead promotes a different pattern of trunk stabilization that involves multiple muscle groups. This insight is crucial for developing rehabilitation techniques, as it implies that training programs incorporating BW should focus on the coordination of multiple muscle groups rather than a single muscle.

Moreover, the similarities observed between intra- and inter-participant conditions suggest that individuals can maintain relatively consistent control of trunk stability, even during atypical gait patterns like BW. While this observation could raise the possibility that humans have an inherent ability to adapt to atypical gait patterns by controlling them as periodic movements, similar to forward walking, this interpretation remains speculative. Such adaptability might reflect the flexibility of the neuromuscular system to adjust to varying demands while maintaining a rhythmic and controlled movement pattern, even when the task involves greater postural challenges, as seen in BW. However, further research is needed to directly examine this potential adaptability.

In summary, although BW placed different demands on ESM activity to FW, the expected increase in ESM activity and variability was not observed. Instead, the results suggest that trunk stabilization may involve a wider range of muscles working together, rather than relying primarily on a single muscle. BW may therefore require a more integrated activation of trunk and lower limb muscles to maintain stability. This finding highlights the need to consider the coordinated role of multiple muscle groups when developing rehabilitation protocols that incorporate BW. However, given the limitations of the study, further research is needed to confirm these findings and to better understand how different muscles contribute to maintaining trunk stability during BW.

The impact of gait speed

An important factor that may have influenced the results is the difference in gait speed between FW and BW. In this study, BW was performed at a slower speed than FW, although the difference was not statistically significant, with median speeds of 0.81 m/s (intra-participant) and 0.87 m/s (inter-participant), compared with FW speeds of 0.99 m/s and 0.94 m/s, respectively. This slower speed in BW may be related to the increased difficulty of maintaining balance without visual feedback. The reduced speed in BW may have contributed to the CoM being positioned higher, as participants likely adopted a more cautious strategy to maintain stability. Additionally, slower speeds may influence the timing and intensity of muscle activation, including that of the ESM, although the lack of differences in cadence and duty cycle suggests that longer stance phases may not fully explain these effects.

Previous studies investigating BW have often used treadmills to control gait speed, which eliminates variability between FW and BW (e.g., Akhil, 2022). In contrast, the current study allowed participants to walk at their self-selected optimal speed, which perhaps reflects more realistic clinical conditions. While this approach provides ecological validity, it also introduces variability in gait speed, which may have affected the interpretation of the results. The slower BW speed in this study could partly explain why ESM activation did not increase as much as expected, as lower speeds reduce the mechanical demands on the muscles. Future studies could benefit from controlling speed more rigorously or comparing multiple speeds to better understand the relationship between speed, muscle activation, and postural control.

Synthesis of CoM, muscle activity, and gait patterns

The findings of this study illustrate the complex interactions between CoM movement, ESM activity, and gait speed in FW and BW, which carry important implications for rehabilitation and exercise programs. Although BW presented distinct challenges for postural control, including greater variability in CoM movement during the single support phase, the anticipated increase in ESM activation was not consistently observed. This outcome may be partly influenced by the slower gait speed during BW, which likely reduced the mechanical demands on the ESM. Slower speeds may encourage a more cautious walking strategy, affecting both the CoM trajectory and the timing of muscle engagement. Given that each par-

ticipant's data for inter-participant comparisons was based on a single trial, these observations should be interpreted as indicative of general trends rather than definitive conclusions about each individual's walking characteristics.

BW is suggested to require different coordination strategies to FW, as evidenced by the unique timing of ESM activity and the variability in CoM movement. These differences in coordination may reflect how the body structures its movements in response to specific task demands, as suggested by a previous report (Dingwell, 2010), which emphasized that variability in walking is not merely random, but rather can be a part of an adaptive strategy to maintain stability in challenging conditions. Despite these differences, participants managed to maintain relatively consistent control of their CoM trajectory, highlighting the adaptability of the neuromuscular system in adjusting to the altered demands of BW. However, the study did not directly measure factors such as energy expenditure or the coordination of other muscle groups, so interpretations regarding the specific compensatory strategies employed should remain tentative.

From a rehabilitation perspective, these findings suggest that while BW can present unique postural challenges and it requires greater dynamic balance and coordination, it may not inherently lead to increased ESM activation. Simply incorporating BW may not be sufficient to substantially enhance ESM strength. Instead, it may be more effective to integrate BW with other exercises that target a broader range of muscles, such as the abdominal and lower limb muscles, to improve overall trunk stability and balance. Additionally, the choice of gait speed during BW could be an important factor in rehabilitation settings. While slower speeds may provide a safer environment for individuals to practice BW, they might not elicit the same level of muscle activation as faster speeds. Future studies should explore the optimal balance between gait speed and muscle engagement to maximize the therapeutic benefits of BW in various clinical settings.

Potential role of central pattern generator mechanisms in backward walking

The findings of this study suggest potential links between the neural mechanisms governing FW and BW, both of which may rely on shared central pattern generator systems. Previous studies (Grasso, 1998; van Deursen, 1998; Zych, 2021) have shown that FW and BW are regulated by similar central pattern generator circuits that generate rhythmic movement pat-

terns at the spinal level. Despite differences in muscle activation patterns, the fundamental rhythm-generating mechanisms remain consistent, allowing for adaptation to varying movement directions.

Furthermore, research on primate locomotion suggests that similar neural pathways may support different forms of gait, including both quadrupedal and bipedal walking (Higurashi, 2019; Pontzer, 2014; Shapiro, 1988). These studies highlight that the neural control mechanisms underlying rhythmic movement are conserved across species and gait types. Understanding BW in humans could therefore provide insights into the adaptability of the neuromuscular system, shedding light on how evolutionary mechanisms have shaped bipedal locomotion. This study primarily focused on the role of the ESM during BW, but future research could explore how central pattern generator mechanisms contribute to adaptations in diverse gait patterns, offering potential implications for both rehabilitation strategies and the study of human evolution.

Study limitations

This study has several limitations that should be acknowledged. First, the small sample size (just one participant for intra-individual analysis and just eight participants for inter-individual analysis) limits the generalizability of the results. In addition, allowing participants to select their own gait speeds introduced variability between FW and BW, which may have influenced muscle activity and CoM variability. Furthermore, this study did not account for differences in age or body type, such as weight, height, and body composition, which could potentially affect gait mechanics. Variations in body type may affect CoM movement and muscle activity during both FW and BW, as body mass or height can alter the dynamics of balance and postural control (Olchowik, 2014). Understanding the relationship between body type and gait is essential for interpreting the individual differences observed in this study. The study focused solely on the ESM, without examining the role of other muscles crucial for balance, such as the abdominal and lower limb muscles. Furthermore, the analysis was limited to walking on flat, level surfaces, thus excluding conditions such as inclined or uneven surfaces that may alter muscle activation patterns. Finally, by excluding individuals with expertise in BW, the study did not account for potential differences in muscle control and CoM dynamics among trained practitioners. Future research should explore controlled gait speeds, assess the long-term effects of

BW in rehabilitation, investigate the influence of body type on gait patterns, and investigate other gait conditions and muscle groups to provide a more comprehensive understanding of BW.

CONCLUSION

This study demonstrated that BW increases CoM variability, especially during the single support phase. While ESM activity was higher in the single support phase during BW, overall activation was not consistently greater than FW. BW thus demands more dynamic balance and coordination, but does not necessarily increase ESM activation.

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REFERENCES

- Akhil VM, Jobin V, et al. Gait variability and IEMG variation in gastrocnemius and medial hamstring muscles on inclined even and uneven planes. *IRBM* 43(5), 447–455, 2022
- Ansari B, Bhati P, et al. Lumbar muscle activation pattern during forward and backward walking in participants with and without chronic low back pain: an electromyographic study. *J Chiropr Med* 17(4), 217–225, 2018 doi: 10.1016/j.jcm.2018.03.008
- Arachchige CNPG, Prendergast LA, et al. Robust analogs to the coefficient of variation. *J Appl Stat* 49(2), 268–290, 2020
- Balasukumaran T, Gottlieb U, et al. Muscle activation patterns during backward walking in people with chronic ankle instability. *BMC Musculoskelet Disord* 21(1), 489, 2020
- Balasukumaran T, Olivier B, et al. The effectiveness of backward walking as a treatment for people with gait impairments: a systematic review and meta-analysis. *Clin Rehabil* 33(2), 171–182, 2019
- van Deursen RW, Flynn TW, et al. Does a single control mechanism exist for both forward and backward walking? *Gait Posture* 7(3), 214–224, 1998
- Dingwell JB, John J, et al. Do humans optimally exploit redundancy to control step variability in walking? *PLoS Comput Biol* 6(7), e1000856, 2010
- Grasso R, Bianchi L, et al. Motor patterns for human gait: backward versus forward locomotion. *J Neurophysiol* 80(4), 1868–1885, 1998
- Grobbelaar E, Kottink AI, et al. Backward compared to forward ground gait retraining in post-stroke patients. *Clin Rehabil* 31(8), 1042–1051, 2017
- Higurashi Y, Maier MA, et al. Locomotor kinematics and EMG activity during quadrupedal versus bipedal gait in the Japanese macaque. *J Neurophysiol* 122(1), 398–410, 2019
- Moon SH, Bae SH. Backward walking training improves gait ability in patients with chronic stroke. *J Phys Ther Sci* 31(5), 420–423, 2019
- Olchowiak G, Tomaszewski M, et al. The effect of height and BMI on computer dynamic posturography parameters in women. *Acta Bioeng Biomech* 16(4), 53–8, 2014
- Den Otter AR, Geurts ACH, et al. Abnormalities in the temporal patterning of lower extremity muscle activity in hemiparetic gait. *Gait Posture* 25(3), 342–352, 2007
- Pontzer H, Raichlen DA, et al. Bipedal and quadrupedal locomotion in chimpanzees. *J Hum Evol* 66, 64–82, 2014
- Rose DK, Winstein CJ. Backward walking training program to improve balance in individuals with chronic stroke. *Stroke Rehabil* 25(5), 125–133, 2018
- Shapiro LJ, Jungers WL. Electromyography of back muscles during quadrupedal and bipedal walking in primates. *Am J Phys Anthropol* 93(4), 491–504, 1994
- Singh RE, White G, et al. Alteration of muscle synergy structure while walking under increased postural constraints. *Cogn Comput Syst* 2(2), 50–56, 2020
- Winter DA. *Biomechanics and Motor Control of Human Movement*. John Wiley & Sons 82–106, 2009
- Wu W, He Y, et al. Effect of backward walking training on knee osteoarthritis: a systematic review and meta-analysis. *Clin Rehabil* 34(1), 3–13, 2020
- Zych M, Cannariato A, et al. Forward and backward walking share the same motor modules and locomotor adaptation strategies. *Heliyon* 7(8), e07864, 2021