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Temporal Gait Measures Associated With Overground and Treadmill Walking in Rett Syndrome

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Abstract

Rett syndrome is a severe neurodevelopmental disorder leading to intellectual impairment and global developmental delays, including difficulty or inability to walk. Assessing differences in temporal parameters and associated variability between overground and treadmill walking is important if gait training is to be incorporated into intervention protocols. Fourteen female patients with Rett syndrome (mean age 10.4 years $\pm$ SD 5.1) were evaluated during overground and treadmill walking. Stride, stance, swing, and double support times, and the variance of these measures, were obtained. Wilcoxon signed-rank tests were used to assess for potential differences between overground and treadmill measures. Treadmill gait resulted in decreases in swing and double support times. When normalized to stride time, treadmill gait displayed an increase in stance time with decreases in swing and double support times. Excepting stance time, treadmill gait resulted in decreased variability, indicating a more regularized gait while walking on the treadmill. These results suggest that treadmill walking can be beneficial for ambulatory patients with Rett syndrome and could be incorporated into a therapeutic protocol designed to maintain the maximum degree of mobility and overall general health as part of a comprehensive health management approach.

Keywords

quality of life, developmental disability, genetics, mutation, rehabilitation

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Rett syndrome is a neurodevelopmental disorder that affects approximately 1 in 10 000 live-born females worldwide, and ~95% of those diagnosed with typical Rett syndrome carry a mutation in the gene coding for methyl-CpG-binding protein 2 (*MECP2*). The condition is characterized by seemingly normal developmental progression up to ages 6 to 18 months, at which point distinct regression in motor, prelanguage, growth, and socialization skills occurs, which is then followed by relative stabilization. Several prominent disabilities in fine and gross motor skills are frequently observed. These include stereotypical hand movements, particularly midline "handwashing" motions, breathing difficulties, bruxism, rigidity/hypertonia, apraxia, ataxia, poor transitions from sitting to standing, and disordered gait and postural control. To date, there is no cure for Rett syndrome and a great need to develop effective pharmacologic and therapeutic interventions. Additionally, the development of reproducible, quantitative clinical measures that can be employed and compared across multiple research sites will be necessary to accurately assess the potential effectiveness of any intervention.[1-3]

The inability to walk often leads to a series of additional physical problems, including contractures of the limbs associated with spasticity and lack of movement, muscle atrophy, scoliosis, and a general lack of physical fitness, including cardiorespiratory fitness. Several authors have suggested physical or movement therapy programs designed to improve overall

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Table 1. Representative Data of Healthy Young Adults and Children From Published Investigations That Included (1) Both Overground and Treadmill Walking Conditions or (2) Investigations That Included Children Whose Mean Age Was Similar to Those in the Current Investigation.

Gait variable	Authors	Healthy participant, mean age and 1 SD	Overground walking, mean and variance	Treadmill walking, mean and variance
Stride time (s)				
	Stolze et al (1997)[15]	28.7 (±5.5)	1.04 (0.005)	1.01 (0.003)
	Stolze et al (1997)[15]	6.6 (±0.5)	1.00 (0.008)	0.91 (0.006)
	Lythgo et al (2011)[16]	10.5 (±0.3)	0.98 (0.006)	–[a]
	Current investigation	10.4 (±5.1)	1.34 (0.116)	1.23 (0.058)
Stance time (%)				
	Stolze et al (1997)[15]	28.7 (±5.5)	60.8 (17.6)	57.9 (8.4)
	Stolze et al (1997)[15]	6.6 (±0.5)	60.6 (24.0)	58.1 (23.0)
	Lythgo et al (2011)[16]	10.5 (±0.3)	57.4 (3.2)	–[a]
	Moreno-Hernández et al (2010)[17]	10.6 (±0.5)	56.4 (2.9)	–[a]
	Current investigation	10.4 (±5.1)	60.2 (59.9)	69.6 (32.5)
Swing time (%)				
	Stolze et al (1997)[15]	28.7 (±5.5)	39.2 (6.8)	42.1 (7.3)
	Stolze et al (1997)[15]	6.6 (±0.5)	39.4 (16.8)	42.0 (25.0)
	Lythgo et al (2011)[16]	10.5 (±0.3)	42.6 (3.2)	–[a]
	Moreno-Hernández et al (2010)[17]	10.6 (±0.5)	43.6 (2.9)	–[a]
	Current investigation	10.4 (±5.1)	39.8 (59.3)	30.4 (32.5)
DS time (%)[b]				
	Stolze et al (1997)[15]	28.7 (±5.5)	21.5 (11.6)	16.0 (4.8)
	Stolze et al (1997)[15]	6.6 (±0.5)	10.7 (4.4)	8.2 (1.7)
	Lythgo et al (2011)[16]	10.5 (±0.3)	14.4 (13.7)	–[a]
	Current investigation	10.5 (±0.3)	29.4 (89.7)	19.3 (27.1)

[a] Treadmill walking was not included in the study. If a variable is not listed for a particular article, that indicates the variable was not reported.
[b] Double support time as a percentage of stride time.

function, including walking for Rett syndrome patients. These therapies have ranged from traditional physical exercises and stretching[4,5] to hydrotherapy.[6] Recently, the use of robotic assisted walking systems that move the lower limbs through a range of motion consistent with that of walking has gained some interest (A. Schwabe, personal communication).

Downs[7] and her colleagues recently reported that 62% of Rett patients were able to walk. Hanks[4] and Cass et al[8] reported that approximately half of the Rett syndrome patients they sampled were able to walk independently. Interestingly, Hanks[4] reported 4 girls who had lost the ability to walk and who were able to regain that ability following training. A large survey revealed that nearly all of the patients assessed were able to walk at least 10 steps, although presumably a large portion of those required assistance.[7] Given that a significant proportion of individuals with Rett syndrome are able to ambulate, it is reasonable to propose that a locomotion training program, including treadmill walking, can be a beneficial component of a comprehensive therapeutic program.

Although there are no theoretical mechanical differences between overground and treadmill walking,[9] there has long been debate concerning the degree that treadmill walking mimics overground walking.[10-12] In addition, although there are multiple reports that several gait measures are modified when treadmill and overground walking are compared,[10,12-14] normalized temporal gait variables (eg, swing, stance, and double-support percentage of gait times) are quite similar when overground and treadmill walking speed is controlled for (see Table 1 for representative values obtained from the literature). Information concerning the degree to which healthy participants modify their temporal gait parameters when moving from overground to treadmill locomotion provides comparison values that Rett syndrome gait investigators can use to evaluate how closely their participants approximate "healthy" gait parameters.

Movement variability is necessary if one is to adapt to ever-changing environments and task goals. Movement variability has traditionally been considered as "noise" (ie, random fluctuations) within a control system as it seeks to minimize the variations about an average movement pattern.[18,19] However, practicing a task results in decreasing variability about a mean performance, with mature movement patterns as generated by healthy, well-practiced individuals demonstrating an optimal level of variability. Too much or too little variability can reflect disorders in the motor control system.[18,19] A recent report has suggested that variability can be addressed by evaluating performance variables (ie, gait velocity) and elemental variables (ie, foot contact forces) thereby combining kinematic and kinetic measures in an innovative approach to investigating movement variability.[20] The interplay between these variables may provide insight into overall gait motor performance. Visual observation of individuals with Rett syndrome who can ambulate indicate that the level of variability associated with their walking is nonoptimal for meeting the necessities to navigate through the everyday environment.

Gait training with motorized treadmills is standard practice with a variety of populations with gait disorders, including those with Parkinson's disease, cerebral palsy, and stroke. Multiple investigations have documented improvements in overground gait parameters with the aforementioned populations resulting from treadmill gait training.[21-26] Although the neurological factors that result in gait difficulties for individuals with Rett syndrome are somewhat different from those associated with Parkinson disease and stroke, treadmill training may prove beneficial to ambulatory patients with Rett syndrome. Decreases in variability during treadmill walking could suggest that a treadmill training protocol may serve to regularize the gait of those with Rett syndrome, potentially transferring to a more mature and stable overground gait pattern. However, a necessary first step prior to implementing extensive treadmill training is to identify potential differences between overground and treadmill walking in the Rett syndrome population.

Despite the proposition that walking programs will provide significant benefits, there remains an extremely limited amount of information regarding walking characteristics of Rett syndrome patients. Although over the last decade or more, Downs and her colleagues have been actively working to develop valid and reliable clinical measures of Rett syndrome walking ability,[27] to date there are no reports of quantitative data that have been obtained during laboratory-based walking activities collected from individuals with Rett syndrome. However, there have been several reports comparing overground versus treadmill walking collected from healthy individuals across a range of ages. Interestingly, there is no clear consensus regarding the differences between overground and treadmill temporal gait parameters. For example, stance time during treadmill walking has been reported to decrease[12,14,15,28] or show no change[29] compared to overground walking, with virtually no change in the variability of this measure. Swing time has displayed decreases[12,30] or no change[15,28,29] when comparing treadmill to overground walking, with none of the authors reporting changes in variability. Finally, double support time has been reported to decrease,[15] increase,[14] or not change between treadmill and overground walking,[12,30] with little change in associated variability. The reasons for these discrepancies are varied, but it is likely this is in large part due to differences in collection protocols. Furthermore, the varied reports provide little guidance regarding expectations concerning potential differences between overground and treadmill walking in patients with Rett syndrome. Finally, age is reported to be associated with temporal gait variables such that stride time, stance time percentage, and double-support time percentage are positively correlated and swing time is negatively correlated with increasing age.[31] Currently the relationship between age and several temporal gait variables is unknown in the Rett syndrome population.

The current study was undertaken to characterize a sample of individuals with Rett syndrome's temporal gait parameters (eg, stride time, double-support time) during both overground and treadmill-driven walking. Obtaining baseline information regarding "typical" walking parameters of individuals with Rett syndrome is a first step in the ability to effectively evaluate any type of therapeutic program aimed at improving walking ability. It was hypothesized that treadmill walking measures would differ from those of overground, including displaying less variance.

Methods

Participants

Fourteen female patients ranging in age from 5 to 20 (mean = 10.4 years, standard deviation ± 5.1) with a diagnosis of typical Rett syndrome as diagnosed using the Neul et al[32] criteria and carrying a pathogenic mutation in the *MECP2* gene, served as participants in this investigation. All are currently receiving treatment at Blue Bird Circle Rett Center at Baylor College of Medicine in Houston, TX. Inclusion criteria included the ability to independently walk while free of any orthotics. None of the participants were taking medications that have been reported to influence basic muscle tone or movement control. The institutional review board of the Baylor College of Medicine and at the University of Houston approved all procedures prior to the initiation of the study. Informed consent was provided by the parent(s).

Data Collection

This study included 2 walking tasks: (1) overground walking on an instrumented walkway, and (2) motorized treadmill walking while secured in a safety harness. The overground walking consisted of walking over a GAITRite instrumented mat 61 cm wide × 4.27 m long (GAITRite). The GAITRite contains embedded pressure-activated sensors that the customized software translates into spatio-temporal gait measures. During testing, if a subject was unable to complete a walkway pass, the trial was stopped and repeated until 4 complete trials were obtained. Behaviors that led to discontinued trials included walking completely off the walkway, stopping in midtrial and refusing to continue walking, or turning and walking back to the starting point. Four passes across the walkway resulted in 10 to 14 strides being available for analysis, depending on the individual's gait pattern.

The treadmill walking was completed on a 2-belt treadmill (Bertec) that had a force plate underneath each belt. Prior to completing this task, reflective makers where placed bilaterally on the hips, leg, knees, ankles, toes, and heels consistent with Vicon's Plug-in Gait lower body marker recommendations. These markers were sampled at 100 Hz by a 12-camera motion capture system (Vicon). The treadmill force plates provided ground reaction forces that were collected at 1000 Hz and were used in conjunction with kinematic data to identify heel/toe strike and toe off.

To complete the treadmill walking task, the participants were first fitted with a safety harness suspended from a frame surrounding the treadmill. They were then positioned such that the 2 feet were on the 2 separate treadmill belts. The harness allowed for unrestrained walking and did not provide postural support unless balance was lost. During data collection, the treadmill was started at a walking pace of 0.1 m/s with the speed being increased by 0.1 m/s approximately every 20 s. The trial lasted until the treadmill reached a speed 0.8 m/s or when it was determined that the subject could no longer keep walking at the speed of the treadmill. This determination was made based on exhibited behaviors (eg, facial and hand gestures, attentional focus, participant no longer trying to walk) and input from the parents indicating that the participant had reached the maximum speed their child could walk. The 20 seconds of collection at each speed resulted in 10 to 14 strides being available for analysis, which, as for overground walking, was dependent on the patient's gait pattern. The block of treadmill strides whose average stride time most closely matched the average stride time of the overground trials was used to compare treadmill data with that obtained during overground walking. The ability to adapt to changing treadmill speeds is the subject of a manuscript in preparation.

The application of the reflective markers used with the camera system took approximately 3 to 5 minutes to complete, and we were concerned this process might lead to some level of anxiety in individuals with Rett syndrome. Therefore, the decision was made a priori to perform the overground walking task prior to the treadmill walking. However, all of our participants were able to complete both walking tasks. Performing the overground walking task first ensured that at a minimum we would obtain some data regarding the participants' walking ability. We have no reason to believe that performing the overground walking task first would have any influence over the walking patterns we obtained during treadmill walking. Both tasks were completed during a single data collection session.

Although individuals with Rett syndrome present a variety of similar behaviors, each individual also displays unique characteristics that may require some adaptations from data collection procedures that would be used with healthy participants. The adaptation required to collect our data set were primarily divided into 2 categories: (1) verbal and visual encouragement by clinical assistants and family members meant to motivate the participant to complete the task and (2) occasional light touch by the clinical assistants to guide the subject during the trial. For example, to encourage the participant to continue to traverse the overground walkway or continue walking on the treadmill, an occasional light touch on the elbow or shoulder was provided by the clinical assistant. Obviously, these adaptations would not necessarily be used while collecting gait-related data with healthy participants but were necessary, and we believe appropriate, adaptations of the procedures in order to obtain reliable data from our participants.

Data Processing and Analysis

The GAITRite software computes a large number of spatiotemporal gait variables by automatically identifying heel strike and toe off events obtained from pressure distribution data from the mat's embedded sensors. The variables selected for this investigation enabled direct comparisons between overground and treadmill walking and are presented below. The kinematic data obtained during treadmill walking was processed using a custom MATLAB (MathWorks) script that filtered the 3-dimensional marker positions using a Butterworth low-pass filter with the cut-off frequency of 6 Hz. Minimum coordinates in the Y direction for markers affixed to both the heels and toes were identified during the static subject calibration. Foot strikes were identified at the minimum position of the heel marker during each gait cycle. In the event of toe-walking, toe marker minimum was used. Toe off was identified as when the toe marker began ascending in the Y direction. Identification of individual strides occasionally required the evaluation of the heel and toe marker data in combination with the force plate data. This resulted from 2 behaviors directly associated with Rett syndrome, those being occasional difficulty stepping on the correct treadmill belt and occasional "toe walking" steps thereby eliminating heel strikes. If these behaviors occurred, it was then necessary to use this "manual" stride identification procedure to determine stride times. In the cases where the participant stepped on the wrong treadmill belt, the above marker procedures in combination with force plate data were used to determine gait cycle events. Because the belt was already loaded by the "correct" leg, the first detectable increase in force beyond that loading level in combination with visual identification of the heel/toe marker making contact with the belt was used to confirm foot strike. This process was reversed to identify toe off when our participants stepped onto the wrong belt.

The gait variables of stride stance, swing, and double support time were obtained from each stride. *Stride time* was defined as the period between one heel/toe contact to the next ipsilateral heel contact. *Stance time* was defined as the time from the moment of heel/toe strike until that same foot leaves the ground (ie, toe off). *Swing time* was defined as the time between when the foot leaves the ground until the next ipsilateral heel/toe strike. *Double support time* was defined as the time that both feet are in contract with the ground during a given stride. Stance, swing and double support times were also calculated as a percentage of stride time. For all variables, an individual participant mean was first calculated, and these means were then used to compute a group mean.

Using the Shapiro-Wilk test for normality, it was determined that several of the variables were not normality distributed. Therefore, the Wilcoxon signed-rank test was used to determine the data from the 2 legs were not significantly different. The data from both legs were then included for further analyses using the Wilcoxon signed-rank test to test for potential group differences between overground and treadmill gait for each of the variables. Pearson r correlations between age and overground variables and age and treadmill variables were calculated. Potential differences in variability was assessed using the F test for equality of variances between overground and treadmill walking for each of the variables. A level of $p < 0.01$ was adopted for significance.

Results

The results of the overground and treadmill walking evaluations are summarized in Figure 1. There were no significant differences between overground and treadmill walking for stride ($Z = -2.277$, NS) and stance time ($Z = -2.095$, NS). However, both swing ($Z = -4.440$, $P < .01$) and double-support times ($Z = -4.304$, $P < .01$) were significantly less during treadmill walking. Stance time percentage was significantly increased during treadmill walking ($Z = -4.327$, $P < .01$), but swing ($Z = -4.327$, $P < .01$) and double support ($Z = -4.463$, $P < .01$) were significantly decreased (Figure 2). Figure 3 displays the variance and the results of the statistical testing of the gait variables. The variance in stride time ($F = 1.945$, $P < .01$), swing time ($F = 2.812$, $P < .01$), and double support time ($F = 2.483$, $P < .01$) was less during treadmill than during overground walking. However, there was no difference in stance time variance ($F = 1.3842$, $P > .01$). When normalized to stride time, only double-support time during treadmill walking displayed less variance compared with overground walking (overground = 89.7 vs treadmill = 27.1 variance, $F = 3.312$, $P < .01$).

Table 1 contains the results from the literature comparing temporal gait measures obtained when treadmill speed was

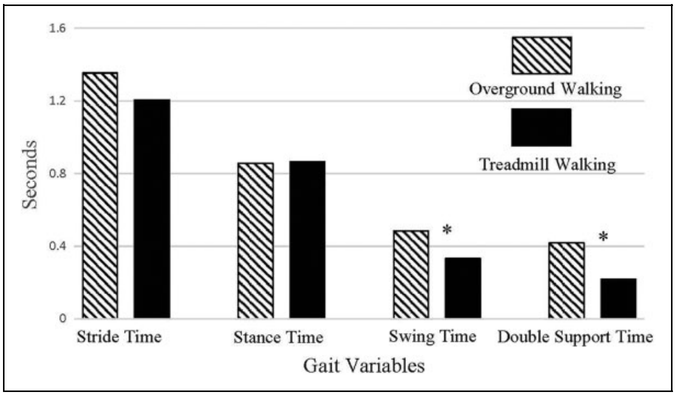

Figure 1. Median overground and treadmill temporal gait measures. Striped bars represent overground data whereas solid bars represent treadmill data. The asterisk represents significant differences at the $P < .01$ level.

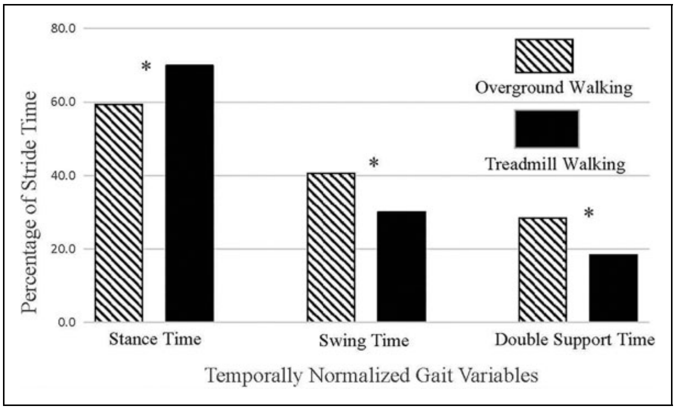

Figure 2. Median overground and treadmill normalized temporal gait measures. Data are represented as a percentage of stride time. Striped bars represent overground data, whereas solid bars represent treadmill data. The asterisk represents significant differences at the $P < .01$ level.

matched to healthy participants' preferred overground speed, or when participant's preferred speed was self-selected for both treadmill and overground walking.[15-17] The average stride time we report is much greater than those found in Table 1. Both stance and swing time percentages during *overground* walking are remarkably similar to those listed in Table 1. However, as in the case of the *treadmill* walking, stance time is greater but swing time is substantially less than previously reported. Conversely, in the current data, double-support time percentage during *overground* walking is substantially greater than previously reported but our value during *treadmill* walking is similar to previous reports.

Turning to the variability associated with our measures, the variance values of our average stride times are much greater than of the variance values previously reported for both treadmill and overground walking. Additionally, we found the overground stride time variance to be significantly greater compared to treadmill walking whereas healthy walkers display little change in stride time variance when moving from

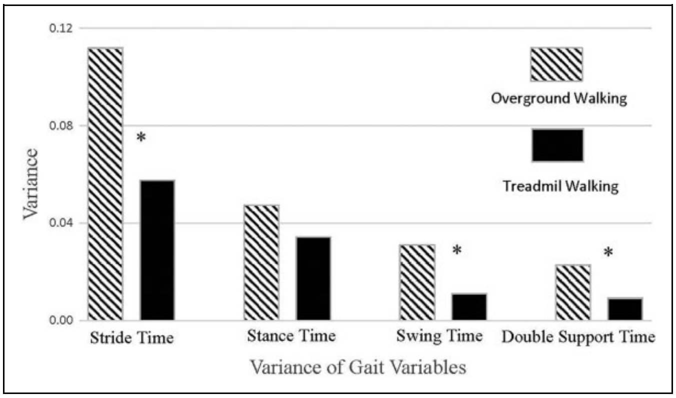

Figure 3. Variance values for overground and treadmill normalized gait measures. Striped bars represent overground data whereas solid bars represent treadmill data. The asterisk represents significant differences at the $P < .01$ level.

overground to treadmill (Table 1). Consistent with the current data, Table 1 reflects little difference in variance between treadmill and overground walking in stance and swing time percentages. However, the variance of these 2 measures in our sample were noticeably greater than previously reported. The variance of the current overground double-support time percentage was noticeably greater than the previous one reported while that same measure for treadmill gait was more consistent with previous reports. Table 2 displays the Pearson r correlation values between age and the gait variables separated by walking mode (ie, treadmill or overground). All correlation values were statistically significant.

Discussion

This report provides gait-related data from a group of 14 participants with Rett syndrome who walked on both a treadmill and overground across an instrumented walkway. There have been no previous reports of comparisons between temporal gait measures obtained during overground and treadmill walking with data obtained from participants with Rett syndrome. The overall finding that treadmill gait is associated with significantly reduced variance indicates that the treadmill serves to regularize the walking pattern of ambulatory females. This suggests that treadmill training incorporated into a therapeutic program for ambulatory Rett syndrome patients may be useful to improve gait performance with the possibility that improved performance transfers to overground walking, as has been reported for patients with Parkinson disease, stroke, and cerebral palsy.[21,22,26]

Comparisons between overground and treadmill locomotion revealed that the median treadmill stride and stance times were not significantly different from the corresponding times obtained during overground walking. Conversely, both swing and double-support times were significantly decreased during treadmill walking. When converted to a percentage of stride time, stance time was greater during treadmill walking. The absence of change in actual stance time, combined with the

Table 2. Pearson *r* Correlation Coefficients Between Age and the Gait Variables for Both Overground and Treadmill Walking.[a]

	Stride time	Stance time, %	Swing time, %	Double support time, %
Overground	0.36	0.45	–0.38	0.62
Treadmill	0.58	0.68	–0.48	0.55

[a]All correlation values were statistical significant.

increase in swing time during overground walking, suggests that the increase in percentage stance time during treadmill walking results from the decrease in actual swing time. Individuals with Rett syndrome appear to move through the swing phase more efficiently while walking on the treadmill and spend a greater proportion of time in stance. The significant decreases in both actual double-support time, and percentage double-support time further indicate that these Rett participants were able to modify their gait patterns relative to overground walking to effectively walk on the treadmill.

Pang and Yang have reported that sensory input resulting from the stance limb being moved backward by the belt is used to regulate the initiation of swing phase.[33,34] During treadmill walking, with its requirement that the participant maintain a cadence that matches the steadily moving belt, more consistent sensory input generated by the stance leg can be used to generate less variable gait patterns. The reductions in variance of all but stance time of our actual temporal gait measures indicates that our participants were able to effectively use the sensory inputs generated during treadmill walking to produce more regularized gait compared to overground walking. The differences may also be consequent to having less precise proprioceptive feedback related to hip extension used to initiate the swing phase during overground walking.

In healthy individuals, overground walking provides the opportunity to control the swing phase and the moment when the foot strikes the ground. Alternatively, during treadmill walking, that freedom is restricted, as the belt speed controls when the foot must strike the ground. Somewhat surprisingly, this may disrupt healthy participants' stability, resulting in the greater double-support times during treadmill locomotion observed in the studies by Yang and King[14] and Wearing et al.[30] Conversely, in the current investigation, significant decreases in swing and double-support times were observed when moving from overground to treadmill walking. Without the benefit of the moving treadmill belt, our Rett syndrome participants displayed longer swing times and spent a significantly longer time in double support. The differences may also be consequent to having less precise proprioceptive feedback related to hip extension used to initiate the swing phase during overground walking. Finally, the increased double-support times during overground walking may serve to provide additional postural stability,[35] but also resulted in more variance. Taken together, the results support the contention that treadmill walking promotes the effective use of cutaneous and proprioceptive input to control gait in individuals with Rett syndrome.

Table 1 reflects that healthy walkers display minimal changes when moving from overground to treadmill walking when commonly used temporal gait variables are converted to a percentage of stride time. Alternatively, it can be observed that our data reflect significant decreases in temporally normalized measures between overground and treadmill walking. Stance time percentage is significantly increased during treadmill walking while swing time percentage is decreased. Given that actual stance times are not different between the 2 walking modes, the change in stance and swing time percentage is a function of the reduced swing time when moving from overground to treadmill walking. This adaptation may reflect the fact that individuals with Rett syndrome may seek to extend the relative amount of time their stance leg is in contact with the treadmill belt in an effort to gain the benefits of more precisely regulated sensory feedback resulting from the consistent belt speed.

Interestingly, although preferred stride times are significantly greater, for overground walking both stance and swing time percentage of stride are very similar in our sample relative to the data presented in Table 1. These measures reflect a degree of neurologic control that mimics that of healthy walkers. However, our participants had far greater double support time percentage when compared to healthy gait as well as significant differences in the actual temporal measures (ie, nontemporally normalized). Thus, although some temporally normalized measures closely match that reported for healthy walkers, there remain important differences in gait control between healthy individuals and those with Rett syndrome.

The overall decrease in variance observed on the treadmill not only suggests effective use of proprioceptive feedback but also that individuals with Rett syndrome are able to resolve the sensory conflict created between visual and vestibular input, resulting from the lack of translation while walking on the treadmill, and that of proprioceptive feedback, generated by the moving limbs.[36] Although it is not known precisely where in the central nervous system this sensory conflict is resolved, based on a number of imaging studies the prefrontal cortex in combination with the sensory cortices have been postulated as likely involved.[36-38] This suggests that the necessary integrating mechanisms are available to support locomotion in ambulatory patients with Rett syndrome.

As displayed in Table 1, healthy individuals display little variability as shown by the small variance in the temporal measures employed in the present study. Although there has been speculation that treadmill walking artificially limits locomotor pattern variability[10] as mentioned previously, that does not appear to be the case for temporal gait measures. This is reflected by the fact that healthy participants display insignificant differences in temporal gait measure variance between overground and treadmill walking. The participants in our study displayed much greater variance relative to participants who are healthy regardless of the walking mode. Moreover, unlike healthy participants, they generally displayed large differences in variance between treadmill and overground walking (Table 1 and Figure 3). High variability can be interpreted as reflecting decreased system cooperation and stability. Decreases in variability then suggest increased system cooperation and stability.[18,19] It is possible that the more consistent sensory input associated with treadmill gait assisted our female patients with Rett syndrome in maintaining a more stable kinematic gait pattern, thereby reducing the amount of variance in the reported temporal gait parameters. The significant correlations between age and our gait variables indicates that from a cross-sectional perspective, the changes in walking patterns follows that reported in the literature.[31] Although the strength of the relationships between age and our variables are less than that reported for healthy walkers, the direction of change, that is, significant positive correlations between age and stride time, stance time percentage, and double-support time percentage, and a significant negative correlation with age and swing time percentage mimics that of healthy walkers. Perhaps with consistent treadmill training, these relationships would be strengthened as overall walking patterns improved.

Despite decreases in the variance between treadmill and overground walking, it would be inaccurate to label the treadmill gait observed in our participants with Rett syndrome as reflecting a healthy, cooperating system producing stable gait behavior. The variance displayed in our measures during treadmill gait far exceeds the variance exhibited by healthy individuals. However, the fact that variance decreased between overground and treadmill gait indicates that overall gait became more regularized on a treadmill.

Limitations of this investigation include the fact that only ambulatory girls who suffer from Rett syndrome have been included in the study as well as a large distribution of participant ages. Interestingly, the large age range enabled us to examine the relationships between age and the gait variables we obtained and determine that there were significant correlations in our data set similar in direction to those previously reported.[31] An additional limitation was that we were unable to determine the reliability of our measures over time, as we only had one opportunity to assess the gait of our participants.

Future research should include opportunities to retest participants to assess the reliability of gait measures, expand gait analysis to kinematic data, and testing to determine if treadmill training can be used to modify gait patterns that transfer to the overground gait of females diagnosed with Rett syndrome. Additionally, comparisons between the effectiveness of robotic-assisted walking devices (eg, Lokomat), and that of treadmill training should be investigated.

Conclusions

This report provides laboratory-based, quantitative gait measures collected from ambulatory females with Rett syndrome during overground and treadmill walking. We have demonstrated that the collection of gait data typically used to evaluate healthy participants can reliably be achieved with small adaptations to standard gait protocols. Differences between treadmill and overground walking suggest that many of the neural mechanisms that support locomotion in both scenarios remain intact and that clinicians and therapists may consider performing evaluations during both tasks to gain greater insight into the underlying abilities of their patients with Rett syndrome. The decreases in variance observed in the present study as our participants moved from overground to treadmill walking indicate that motorized treadmill walking serves to regularize the lower limb motions associated with walking, and therefore may be useful as a therapeutic intervention. These findings support further studies of the potential benefits of treadmill gait training on the overall health status and promotion of more efficient overground walking in individuals with Rett syndrome.

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Author Contributions

CL and BS conceived and participated in the study design. CL, BS, and DY participated in the acquisition. CL, BC-L, and DY participated in data analysis. CL and BS participated in data interpretation. CL and BS drafted the manuscript. All authors critically revised and approved the final version for publication.

Declaration of Competing Interests

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Supplemental Material

Supplementary material for this article is available online.

Ethical Approval

This study was approved by the Institutional Review Boards of the Baylor College of Medicine (H-35835) and University of Houston (15267-01-5962)

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