Are Gait Biomechanics Related to Physical Activity Engagement? An Examination of Adolescents with Autism Spectrum Disorder

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ABSTRACT

BENNETT, H. J., S. I. RINGLEB, J. BOBZIEN, and J. A. HAEGELE. Are Gait Biomechanics Related to Physical Activity Engagement? An Examination of Adolescents with Autism Spectrum Disorder. *Med. Sci. Sports Exerc.*, Vol. 54, No. 3, pp. 447–455, 2022. **Purpose:** Adolescents with autism spectrum disorder (ASD) rarely meet physical activity (PA) guidelines, thus not reaping associated health benefits. Although many barriers exist, abnormal or inefficient gait biomechanics could negatively impact engagement in PA. This study has two purposes: first, to compare total body mechanical work between adolescents with ASD and neurotypical age-, sex-, and body mass index–matched controls, and second to determine whether gait biomechanics are significantly related to engagement in PA. **Methods:** Twenty-five adolescents (age, 13–18 yr) with ASD and 17 neurotypical controls (eight with ASD had no match) participated in the study. Three-dimensional motion capture and force platforms were used to record and analyze gait biomechanics at self-selected speeds and a standardized $1.3\ \text{m}\cdot\text{s}^{-1}$. Total body mechanical work (sum of joint works across lower extremity, low back, torso, and shoulders) was compared between groups ($n = 17$ for each) and speeds using a mixed model analysis of variance. Average daily light PA, moderate to vigorous PA, and total PA was recorded for the entire data set with ASD using triaxial accelerometers worn for 1 wk. Regression analyses were performed between work, stride time variability, speed, and stride length with each PA variable. **Results:** Adolescents with ASD generated 9% more work compared with the controls ($P = 0.016$). Speed and stride length were significant regressors of light PA, moderate to vigorous PA, and total PA, explaining greater than 0.20 variance ($P < 0.02$ for all regressions). **Conclusions:** Although adolescents with ASD walked with significantly greater work, the complex full-body variable is not significantly related to engagement in PA. In agreement with research spanning multiple populations and ages, speed and stride length are indicative of PA engagement in adolescents with ASD. **Key Words:** GAIT, BIOMECHANICS, PHYSICAL ACTIVITY, AUTISM SPECTRUM DISORDER, WALKING, ENERGETICS

For all youth, regular engagement in physical activity (PA) is important to promote and maintain physiological and psychological health (1). In addition to these health-related benefits, adolescents with autism spectrum disorder (ASD) may also experience improvements in social skills and sleep quality as a result of regular PA engagement (2–4). Unfortunately, adolescents with ASD have been identified as being especially at risk for not engaging in sufficient amounts of PA (4–6). For example, in an analysis of data from the 2016 National Survey of Children's Health (5), Healy and colleagues identified that just 10% of adolescents age 13 to 17 yr with ASD met explicated PA guidelines of 60 $\text{min}\cdot\text{d}^{-1}$. In addition, adolescents with ASD tend to participate in less team or individual sports than their neurotypical peers, which may reduce opportunities to engage in PA (6). Because adolescents with ASD tend not to engage in PA, they are likely failing to reap potential physiological and psychological benefits (5). Rather, it appears that adolescents with ASD spend most of their leisure time engaged in various sedentary activities (e.g., using personal computers, watching television) (5). Supporting this, in the aforementioned study by Healy and colleagues (5), adolescents with ASD age 13 to 17 yr were significantly less likely to meet explicated screen-time recommendations of $<2\ \text{h}\cdot\text{d}^{-1}$ than their neurotypical peers in a population-based US sample. Although numerous factors have been identified that may influence PA among adolescents with ASD (e.g., lack of sociocommunication skills, social exclusion from activities), one factor that has gained substantial attention is motor domain deficiencies (7). However, research examining motor domain deficiencies tends to be rooted in a fundamental motor skill perspective and has yet to be explored from other perspectives.

Although there are clearly numerous PA options for adolescents with ASD to participate in, we focused specifically on

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walking for this analysis for several reasons. First, walking is a highly popular form of light PA (LPA) that is linked to a variety of favorable health-related outcomes, such as enhanced fitness, reduced disease risk, and improved mental health (8,9). In addition, recent research has found that engagement in LPA, such as walking, is comparable to the mortality benefits assumed by engaging in moderate-to-vigorous PA (MVPA). Third, prior research has identified that although team sport participation and school-based physical education are generally considered a favorable PA option for neurotypical adolescents, adolescents with ASD appear to have less favorable views about these activities (6,10,11). For example, in a study comparing PA enjoyment, barriers, and beliefs among adolescents with autism and neurotypical peers, Stanish and colleagues (10) noted that significantly fewer adolescents with ASD enjoyed team sports, as well as physical education, than their peers. Importantly, no differences were found in perceptions toward walking and individual activities between adolescents with ASD and neurotypical peers in the previous study (6). Examples of discontent toward physical education in particular was further exemplified in a recent study by Haegele and Maher (11), where adolescents with ASD reported experiences of marginalization and isolation in physical education classes, leading them to have unfavorable views and disengage from activities within these classes.

Walking is a low load and energetically efficient activity of daily living. However, underlying health issues and aberrant gait mechanics can negatively impact the ease of this mode of PA by increasing the effort required to perform the task. Thus, an important consideration for investigations on the engagement of PA is the energy expenditure (or effort) required for a person to perform the activity. From a biomechanics perspective, energy expenditure can be derived using total mechanical work (12). Aberrant gait mechanics, such as increased movement and loading outside of the sagittal plane, slower walking speeds, and increased coordination variability, which have all been found in persons with ASD (13–16), could increase mechanical work and, thus, present an unexpected biological/physical barrier to PA.

The current literature indicates that children, adolescents, and adults with ASD choose to walk at slower speeds, with reduced stride lengths, and with increased stance widths compared with neurotypical controls (17–21), which can negatively impact efficiency (i.e., increase mechanical work per unit mass and distance traveled). In addition to spatiotemporal characteristics, joint-level and full-body mechanics differ between those with ASD and controls (22–26). For instance, adults with ASD demonstrate a reduced ability to attenuate head accelerations/oscillations (27), adolescents with ASD walk with increased frontal plane hip moments (16), and children exhibit increased coordination variability (23,24) when walking at self-selected speeds. It is likely that several of these alterations in gait mechanics would increase total body mechanical work. An increase in, or even a similar amount of, work against the reportedly reduced stride lengths would also indicate reduced efficiency in persons with ASD compared with neurotypical controls.

Although we have obtained an increased amount of knowledge regarding persons with ASD through PA and biomechanics fields separately, research focused on improving the health and well-being of persons with ASD (a goal of all areas of exercise science) could greatly benefit from finding connections between these two fields. To this end, previous research has found connections between gait and balance with PA measures in other populations. Self-selected walking speed in older women (28), stride time variability (standard deviation of stride time) in persons with a visual impairment and sighted healthy/fall-prone adults (29,30), and local dynamic stability in persons with a visual impairment and sighted healthy/fall-prone adults (30,31) are significantly related to PA level. Group-wise comparisons, including persons with a visual impairment and sighted controls, have found those who are more active tend to walk at faster speeds and demonstrate improved balance/postural stability (30,32,33). Although those with ASD may not typify "clinical" populations, where injury, neurological disorders, or age have negatively impacted their functioning, those with ASD exhibit limitations in motor control and choose to walk at slower speeds with shorter strides, increased variability, and with decreased stability (17,19,23,34,35). Research has also shown that engaging in PA promotes angiogenesis and has shown to increase vascular function in the motor cortex (36). As such, it is important to determine if deficits in motor control specific to common forms of PA (e.g., gait biomechanics) are an additional, previously unseen physiological barrier to engagement in PA. Knowledge on the relationship between gait biomechanics could be used to guide physical education and rehabilitation programming on previously unseen factors impacting engagement in PA, such as improving stability (decrease stride time variability), encouraging proper stride/cadence balance, and/or walking efficiency (decrease work) (37,38).

The purposes of this study were to (1) compare mechanical work between persons with ASD and matched controls at self-selected and standardized speeds, and (2) determine if gait biomechanics are related to PA (MVPA and total PA minutes) in persons with ASD. We hypothesized that persons with ASD would generate greater mechanical work compared with neurotypical controls, regardless of speed, but markedly more work than controls at the standardized speed. We also hypothesized that adolescents with ASD who generated less work during walking and choose to walk at faster self-selected speeds and with longer stride lengths would engage in more PA.

METHODS

Participants. This study was approved by the University Institutional Review Board. Power analyses were performed using results from studies focusing on persons with ASD for group main effects and studies of neurotypical persons at differing speeds. Work data do not currently exist for persons with ASD. Therefore, we used ankle, knee, and hip kinematic and kinetic data from three studies comparing persons with ASD and controls (26,39,40) for our power analyses (G*Power [41,42]). Effect sizes (Cohen's *D*) for peak ankle moments ranged from

	Age (yr)	Sex (M/F)	Mass (kg)	Height (m)	BMI (kg·m^{-2})	Speed (unitless)
ASD	14.7 ± 1.5	12/5	56.2 ± 16.1	1.65 ± 0.11	20.1 ± 3.9	0.46 ± 0.09
CONTROL	14.5 ± 1.4	12/5	59.7 ± 12.9	1.71 ± 0.07	20.3 ± 3.6	0.50 ± 0.09

Age (yr), mass (kg), height (m), and BMI are presented as mean ± standard deviation. Data represent the age-, sex-, and BMI-matched groups of persons with ASD (n = 17) and controls (n = 17). BMI, body mass index

0.83 (40) to 1.62 (39), knee range of motion ranged from 1.46 (26) to 1.61 (39), and hip range of motion from 0.60 (39) to 0.96 (26). Analyses indicated that 3 to 20 participants per group would be needed for similar group main effects between those with ASD and controls. Correlation/linear regression power analyses were also performed using the strong relationship between stride time variability and PA found in persons with a visual impairment (R^2 = 0.61; [30]), indicating eight persons would be required. Increasing our participant group to greater than 20 would improve our sensitivity to less than 0.28. Twenty-five adolescents with ASD (13–18 yr) were recruited from the surrounding community using word of mouth, posted flyers, and e-mails. Seventeen age-, sex-, and body mass index–matched neurotypical controls (one-to-one matching; eight with ASD had no match before COVID-19 restrictions) were also recruited to participate. Participation criteria included no reported musculoskeletal injury within 6 months and a lack of joint disease/replacement. Furthermore, all participants were required to have an IQ > 70 and participants could not be pregnant at the time of the study. To be included in this study, parents of adolescents with ASD presented medical or educational service documentation confirming an ASD diagnosis. Adolescents with ASD were required to provide documentation confirming a diagnosis of ASD. Inclusion criteria for neurotypical controls included a lack of social, physical, or sensory impairment. All participants, and their legal guardians if younger than 18 yr of age, provided consent and assent. Participant demographics are provided in Table 1.

Motion capture protocol. Participants were asked to don spandex shorts and a standardized shoe (Under Armor Micro G Pursuit). Next, reflective markers were placed bilaterally on the bony endpoints of the upper arms (acromions and humeral epicondyles), trunk (acromions and iliac crests), pelvis (anterior and posterior superior iliac spines), thighs (greater trochanters and femoral epicondyles), shanks (femoral epicondyles and malleoli), and feet (malleoli and metatarsal heads). Clusters of markers attached to rigid shells were secured to the lateral aspect of the upper arms, thighs, and shanks, and posterior aspect of the trunk, pelvis, and shoes (heels) (16). After preparation for motion capture, participants performed several warm-up trials, which required them to walk across the laboratory space at a speed typically used for walking to/from classes (43,44). Self-selected speeds were recorded during warm-up trials using two pairs of photocells connected to an electronic timer (Lafayette Instrument Co., Lafayette, IN). Next, participants with ASD were asked to walk through the laboratory space within ±5% of their self-selected speed and a standardized speed of 1.3 m·s^{-1}. The order was not randomized for those with ASD to reduce the possibility of setting an "expected" speed. Neurotypical controls were asked to walk at their self-selected speed and the standardized 1.3 m·s^{-1} in a randomized order. Ten trials (five strides per leg) that were within the speed range and included full foot contact for three consecutive steps (i.e., a full stride) were recorded for analysis. Spatiotemporal characteristics for each group can be found in Table 2.

Kinematic (marker trajectory) and force data were imported into Visual3d (version 6, C-Motion, Inc.). Data were lowpass filtered using a fourth order Butterworth filter with a cutoff frequency of 8 Hz (43–46). A 10-segment inverse-dynamics model (bilateral upper arms, trunk, pelvis, and bilateral lower extremity), where each segment had six degrees of freedom, was created for each participant. An *X–Y–Z* (flexion–adduction–internal rotation) Cardan rotation sequence and the right-hand rule were used for angular kinematics and kinetics. Internal joint moments and powers were computed using bottom-up inverse dynamics and expressed in the distal segment coordinate system. Kinematic and kinetic waveforms were temporally cut to include a full stride, beginning with foot contact (vertical ground reaction force >20 Hz) and ending with foot-off (vertical ground reaction force <20 Hz). Stride time variability was calculated as the standard deviation among trials of the period from foot contact to foot off (30,31). Self-selected and the 1.3 m·s^{-1} walking speeds were normalized to the square root of leg length times gravity (47).

Positive and negative work were calculated as the integral of the positive and negative power curves for each joint (bilateral shoulder, hip, knee, and ankle joints and the lower back joint) and the trunk segment, respectively. Total body mechanical work was derived as the sum of the absolute value of the positive and negative mechanical works across the joints and trunk. Mechanical work was normalized to body mass times stride length for the self-selected (W_SS) and standardized 1.3 m·s^{-1} (W_13) speeds.

PA protocol. PA was measured using ActiGraph GT3x triaxial accelerometers (ActiGraph, Pensacola, FL). A 15-s epoch

TABLE 2. Group demographics of gait biomechanics and PA variables used in regressions.

	Speed (unitless)	SL (unitless)	STV (s)	Work (J·kg^{-1}·m^{-1})	LPA (min)	MVPA (min)	Total PA (min)
ASD (n = 25)	0.45 ± 0.05	1.66 ± 0.14	4.6 ± 3.0	1.94 ± 0.26	195.9 ± 62.6	29.0 ± 15.4	224.9 ± 69.2
CONTROL (n = 17)	0.50 ± 0.09	1.72 ± 0.22	6.1 ± 2.7	1.85 ± 0.14	172.3 ± 48.5	38.9 ± 18.9	211.1 ± 50.6

Speed, SL, STV, work walking at self-selected speed, LPA, MVPA, and total PA are presented as mean ± standard deviation.
STV, stride time variability; SL, stride length.

was used for all participants. Validated cut points for youth by Evenson et al. (48) were used to process the data. The cutoff criteria included (a) sedentary activity (0–100 counts per minute), (b) light PA (LPA; 101–2295 counts per minute), (c) moderate PA (2296–4011 counts per minute), and vigorous PA (4012+ counts per minute). Accelerometer data were downloaded, screened, and processed using ActiLife 6 software and were included in the analysis if monitors were worn for a minimum of four consecutive days, with at least 8 h of wear time per day (49,50). Measures of LPA and MVPA (sum of moderate and vigorous categories) in minutes were averaged across days the accelerometer was worn.

Statistical analyses. Descriptive statistics of each variable were generated to investigate the assumptions of each test before performing statistical procedures (SPSS Statistics version 26, IBM). Box and whisker plots are provided for total mechanical work in Figure 1. A mixed model two-way analysis of variance was used to compare mechanical work between groups (ASD/controls) across speeds (self-selected speed and 1.3 $m \cdot s^{-1}$) for only those with ASD that had a matched neurotypical control ($n = 17$ per group). The focus variable, W_SS, had a normal distribution (Shapiro–Wilk statistic >0.90 and $P < 0.05$) and passed all ANOVA assumptions. The alpha level for the ANOVA was set at 0.05. *Post hoc* independent samples *t* tests were used to examine interactions, if present, for mechanical work/PA (alpha set at 0.02, assuming two additional tests).

The relationship among gait biomechanics variables (W_SS, speed, stride length, and stride time variability) and each PA variable (LPA and MVPA) was first visually assessed using scatter plots. Linear, logarithmic, power, or quadratic fits were implemented where appropriate. Linear regression analyses were then performed using built-in software function (SPSS). Regression assumptions of linearity, homoscedasticity (scatterplot of residuals/expected values), outliers/influential datapoints (standardized DfBeta> 2/sqrt(n)), and distribution of the residuals (via quantile-quantile plots of residuals) were assessed, and any violations were reported. For both groups, regressions with MVPA displayed linearity, heteroscedasticity, and influential datapoint issues. Moderate-to-vigorous PA was transformed using logarithm base 10, which remedied most linearity and heteroscedasticity issues. ANOVA results for each regression are reported, including F statistic, P value, and R^2. When strong influential datapoints were found, ANOVA results are reported for the model with/without the influential datapoints. To control for the effects of multiple comparisons, the Benjamini–Hochberg procedure was implemented with a false discovery rate of 0.06 (51).

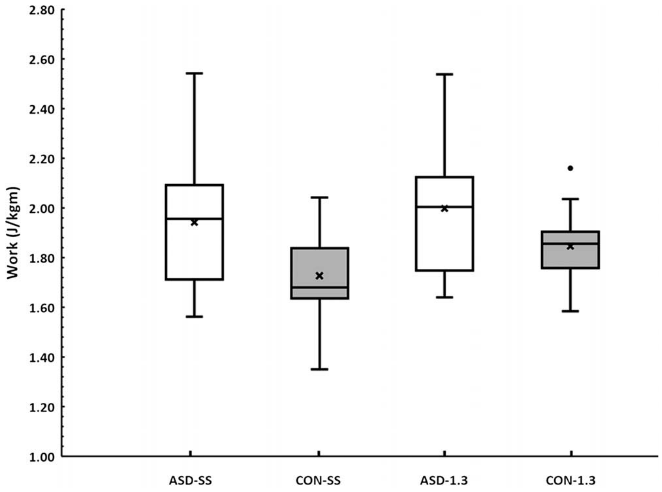

FIGURE 1—Box and whisker plots of total mechanical work. Total body mechanical work W_SS and the standardized W_SS speeds were normalized to body mass times stride length and are provided for those with ASD and CON. The "x," *horizontal line*, top of *boxes*, bottom of *boxes*, and *filled circles* represent the mean, median, upper quartile, lower quartile, and outliers (if present), respectively. CON, controls.

RESULTS

Group comparisons of work. There was no significant group–speed interaction (F (1,32), 2.720; $P = 0.109$, $\eta_p^2 = 0.078$) and no significant speed main effect (F (1,32), 1.329; $P = 0.258$; $\eta_p^2 = 0.040$). A significant group main effect was found (F (1,32), 6.463; $P = 0.016$; $\eta_p^2 = 0.168$). Adolescents with ASD walked with 9% greater work (mean difference, 0.16 $J \cdot kg^{-1} \cdot m^{-1}$) than the neurotypical controls (Fig. 1). Work contributions by each joint and the torso segment are provided in Figure 2.

Work–PA. The W_SS was not significantly related to LPA or MVPA for either group (all $P > 0.05$, $R^2 < 0.10$).

Stride time variability–PA. A significant log-linear regression was found for stride time variability–LPA ($F = 5.870$, $P = 0.024$; Fig. 3) for those with ASD. Stride time variability was not significantly related to MVPA for those with ASD nor for LPA or MVPA for controls (all $P > 0.05$, $R^2 < 0.10$).

Speed–PA. For those with ASD, an influential datapoint was found for speed–LPA and speed–MVPA (standardized DfBeta, >1.0 and >2.0, respectively). With the influential datapoint removed, a linear regression was found for speed–LPA ($F = 5.837$, $P = 0.024$; Fig. 4A) and for speed–MVPA ($F = 7.929$, $P = 0.010$; Fig. 4B). Table 3 provides regression statistics with the full data set.

For controls, two influential datapoints each were found for speed–LPA (standardized DfBeta >0.60). With the influential datapoints removed, a linear regression was found for speed–LPA ($F = 16.135$, $P = 0.001$; Fig. 4C). Table 3 provides regression statistics with the full data set. No significant regression was found for speed–MVPA ($P > 0.05$, $R^2 < 0.10$).

Stride length–PA. For those with ASD, a significant linear regression was found for stride length–LPA ($F = 10.360$, $P = 0.004$; Fig. 5A). A significant multiple linear regression (quadratic) was found for stride length–MVPA ($F = 8.872$, $P = 0.001$; Fig. 5B). Both stride length and stride length^2 were significant regressors ($P < 0.02$).

For controls, two influential datapoints were found for stride length–LPA (standardized DfBetas >0.50). With the influential datapoints removed, a significant linear regression was found for stride length–LPA ($F = 19.080$, $P = 0.001$; Fig. 5C). Table 3 provides regression statistics with the full

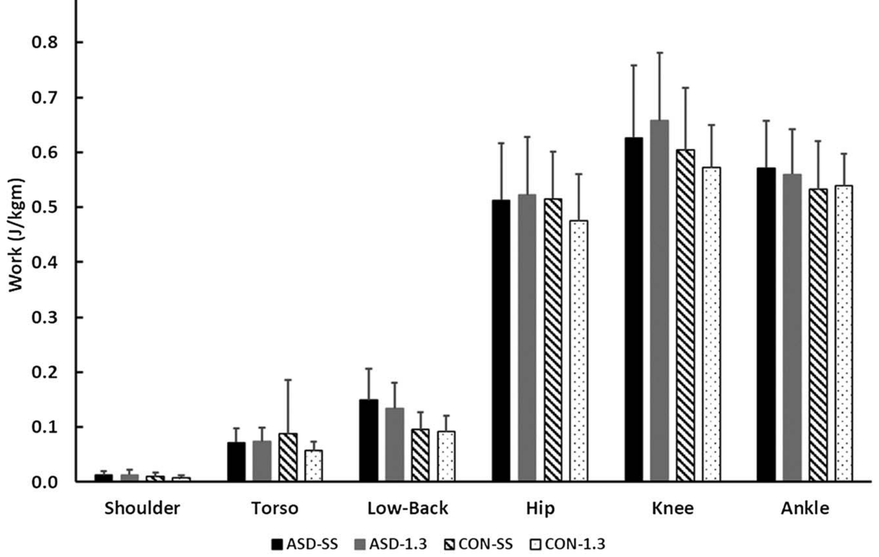

FIGURE 2—Contributions of each joint and the torso segment to total body work. Columns represent the ensemble means of the summed positive and negative (absolute value) work per joint and the torso segment across the full stride (foot contact to foot off). Work (joules) was normalized to the product of body mass (kg) and stride length (m). Data are reported for those with ASD and the CON W_SS and the standardized W_1.3.

data set. No significant relationship was found for stride length–MVPA ($P > 0.05$, $R^2 < 0.10$).

DISCUSSION

This study aimed to compare mechanical work between adolescents with ASD and neurotypical controls and to examine the relationship between biomechanics and PA measures in adolescents with ASD. Our first hypothesis was partially supported: adolescents walked with greater work, regardless of speed. However, there was no significant group–speed interaction. Our second hypothesis was that gait biomechanics variables would be significant predictors of PA measures in those with ASD, where those who walk more efficiently (less work) and at faster speeds engage in greater PA. Our major variable, mechanical work, was not a significant regressor for LPA or MVPA for either group. Speed and stride length were related to engagement in PA for both groups, but with opposing relationships per group.

Although scientific research and clinical reports have advanced our understanding of ASD, our knowledgebase is still in its infancy. Only within the last decade has gait-related research on ASD really emerged (52,53). Given the broad-ranging social and behavioral characteristics of ASD, gait biomechanics of persons with ASD are best considered as "heterogeneous" (so termed because direction of results are variable) for both intergroup and intragroup comparisons (16,22–24,54–57). The current study builds on our existing knowledge by examining a previously unexplored area (energetics) in persons with ASD and doing so at both matched and self-selected speeds, a feature which was generally ignored in the previous literature. Total mechanical work is the superposition of the joint-level mechanics. Thus, mechanical work allows us to discern whether differences in joint-level mechanics, such as increased ankle and hip loading (16,21,22,26,39,40,55), affect measures like efficiency and task performance. In this study, we found that adolescents with ASD required a 9% increase in mechanical work to walk at both self-selected and standardized speeds. As expected, most of the work arose from the lower extremity joints (Fig. 2). Although comparing joint and segment level works was not an aim of the current study, it is apparent that differences occur because of a cumulative effect from multiple joints and not necessarily from a singular location (e.g., from the ankle due to equinus gait sometimes found in those with ASD). This "whole body" sentiment agrees with the current literature, where differences in joint-level mechanics are reported across the ankle, knee, and hip joints (16,21,22,26,39,40,55). In conjunction with the current literature, the findings of the current work illustrate that those with ASD walk with increased

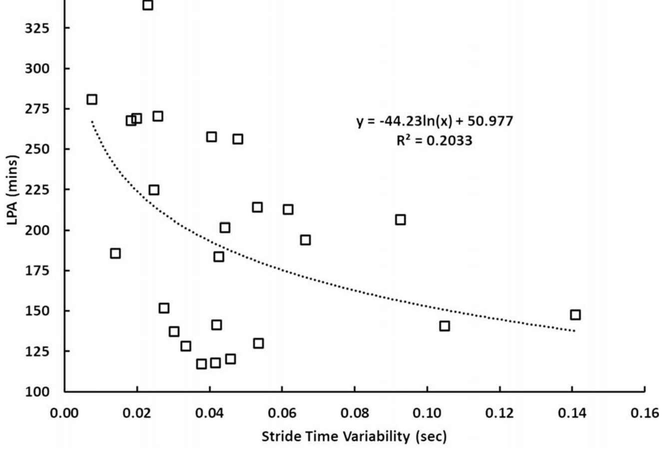

FIGURE 3—Stride time variability–PA scatterplot for those with ASD. Stride time variability–LPA scatterplot is provided for those with ASD. The *dotted line* represents the linear regression fit. The corresponding equation is also provided.

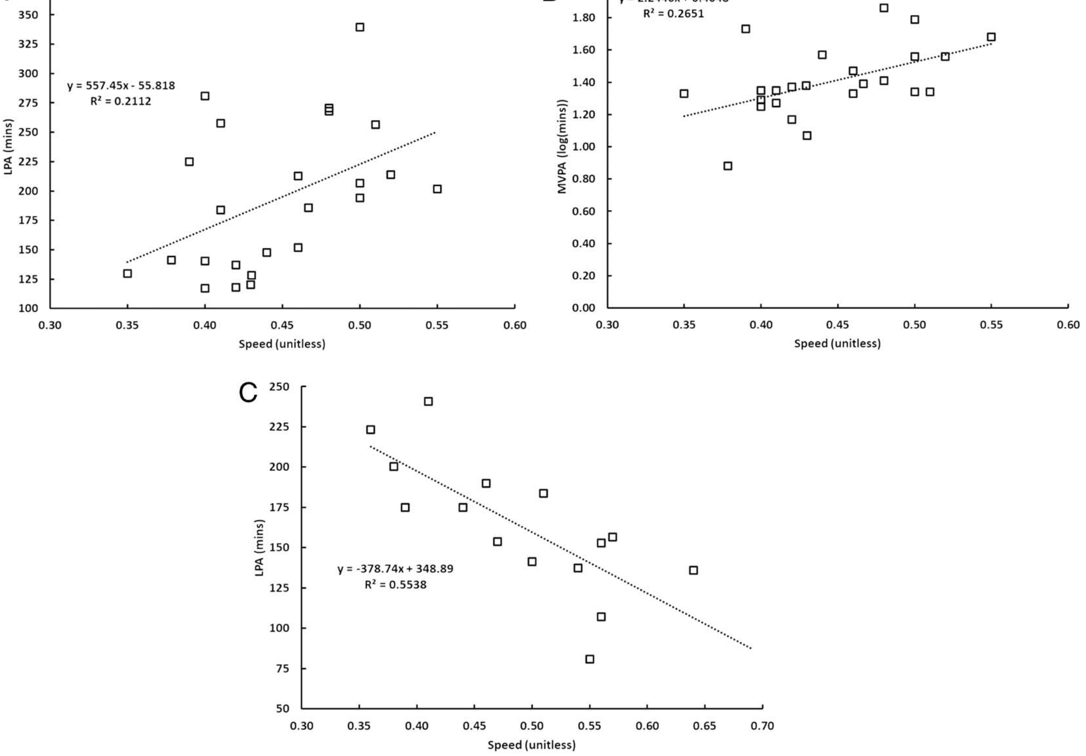

FIGURE 4—Speed–PA scatterplots for those with ASD (A, B) and controls (C). Speed–LPA (A) and speed–MVPA (B) scatterplots are provided for those with ASD. Speed–LPA scatterplot is provided for controls (C). The *dotted line* represents the linear regression fit. Corresponding equations are also provided.

mechanical effort not only as a function of their slower walking speeds and shorter strides (the most reported differences in the literature) but also likely because of the additive effects of suboptimal gait mechanics across the entire system.

Regardless of population, engagement in PA is a crucial part of a healthy lifestyle. Although many barriers to PA have been identified previously, the influence of gait biomechanics and energetics on walking, the most common mode of PA, went previously unexplored. Targeting this deficit of research in persons with ASD, this study aimed to determine gait biomechanics relationships to PA engagement. The lack of significant relationship between work and PA could stem from the variability in each variable. An assumption of the work–PA relationship in persons with ASD is that intragroup variability would exist similarly in all variables. However, LPA and MVPA variability was much greater than the variability in work (Table 2). In agreement with previous work, stride time variability was significantly related to LPA, indicating that those with more stable stride to stride mechanics are more physically active (29,30).

Whereas walking speed and stride lengths are more visible, providing a visual model to which those with ASD may replicate, total body mechanical work and interstride variation variables are complex and less evident to the naked eye. As such, variations in step width and joint-level mechanics certainly affect mechanical work but could be overcome/implemented to attain an expected speed and stride length. Although those with ASD required more work to walk than their neurotypical counterparts, both groups can also be assumed to be healthy community ambulators. Therefore, small within-group variations in work may not translate to a significant impact on PA engagement (engagement was quite low for both groups; Table 2). Simply put, all persons demonstrated the ability to walk and thus could engage in PA without a significant physiological limitation. Future work should consider more vigorous forms of locomotion/activity, which could elicit relationships beyond those found during low-load walking analyzed here. It is also important to note that although measures of mechanical work are sensitive enough to detect group differences within the current study and previous work (12), mechanical work is not the same as metabolic energy expended. Therefore, it is possible that energetic variance within the ASD group was not fully captured using the mechanical work method (12). Future research is required to examine the relationship of metabolic energy and PA level in persons with ASD.

In contrast, this study did find that self-selected walking speed and stride length are related to engagement in both MVPA and total PA. Although we cannot answer the “chicken or the egg”

TABLE 3. Regression statistics using full data sets when influential datapoints were found.

Groups	Variables	Statistics (F, P, R^2)
ASD	SP-LPA	6.745, 0.016, 0.227
	SP-MVPA	4.301, 0.049, 0.158
CON	SP-LPA	5.172, 0.038, 0.256
	SL-LPA	5.450, 0.034, 0.267

SP, speed.

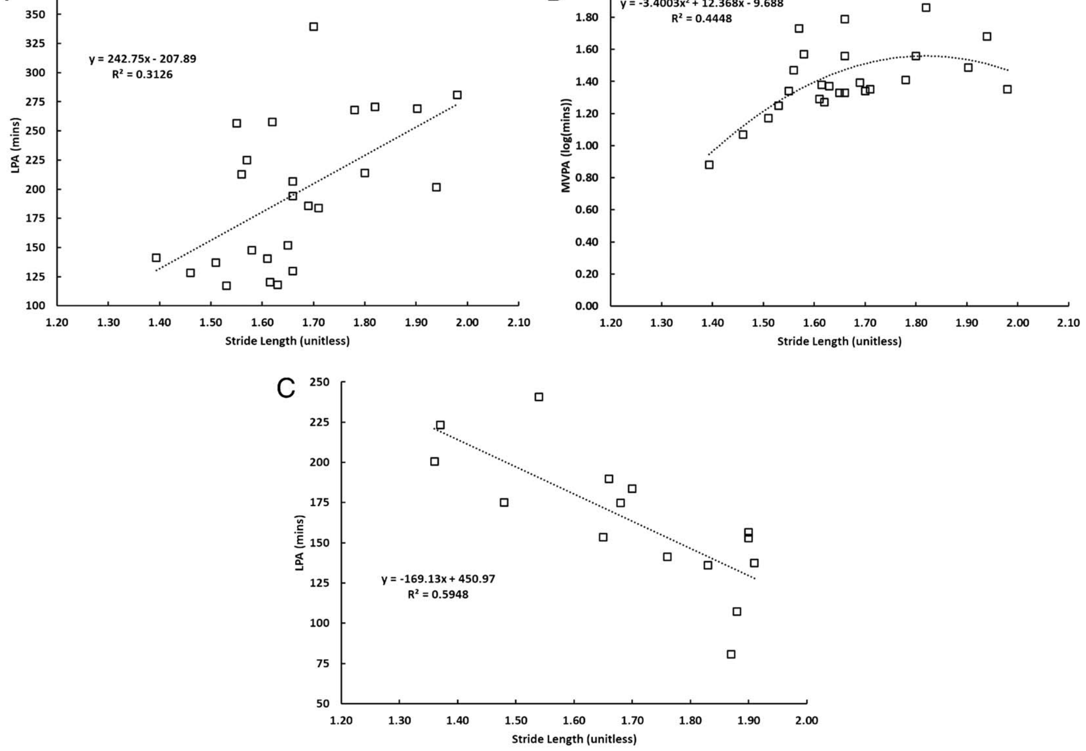

FIGURE 5—Stride length–PA scatterplots for those with ASD (A–B) and controls (C). Stride length–LPA (A) and stride length–MVPA (B) scatterplots are provided for those with ASD. Stride length–LPA scatterplot is provided for controls (C). The *dotted line* represents the linear regression fit. Corresponding equations are also provided.

question regarding spatiotemporal characteristics and PA, the current study builds on the existing evidence that speed and stride length are strong markers of physical and mental health across several populations (29,30). The connection between spatiotemporal characteristics and MVPA is interesting, as walking does not fit the physical rigor for MVPA but has been found in younger and older women (28). Thus, it is apparent that the importance of spatiotemporal characteristics extends beyond just similar low-load activities (i.e., to MVPA). The quadratic form of the stride length–MVPA relationship is an unexpected finding considering the linear fit of the speed–MVPA relationship. Although faster walking speeds were attained using longer stride lengths in controls (Fig. 6A), and thus correlation analyses should be similar between variables, those with ASD did not demonstrate a strong speed–stride length relationship (Fig. 6B). Further research is required to understand the speed–stride length–cadence relationship in persons with ASD. Overall, the findings of this study illustrate that educational/rehabilitation programming for adolescents with ASD should consider focusing on increasing comfort with their environment and confidence during walking which could increase self-selected speeds and stride lengths.

Major differences were found in the biomechanics–PA relationships between adolescents with ASD and controls. Although the relationship between spatiotemporal characteristics and PA for those with ASD followed an expected trend (28,30,31), the

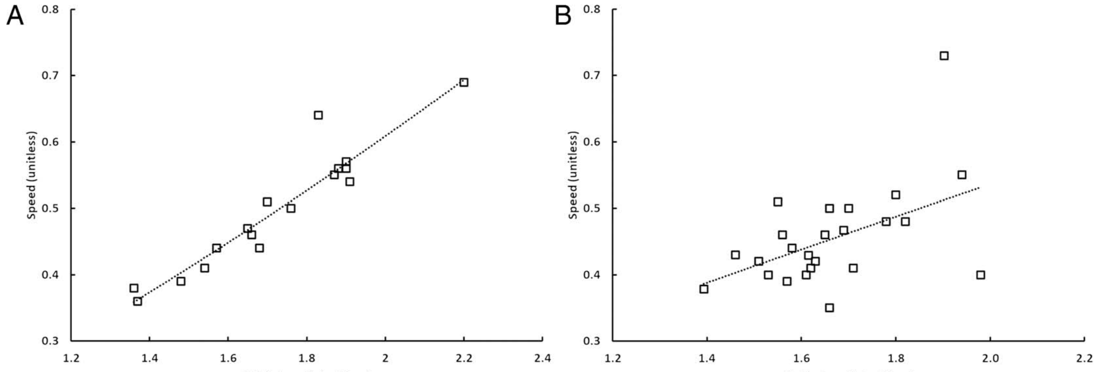

FIGURE 6—Stride length–speed scatterplots for controls and those with ASD. Scatterplots are provided for stride length–speed for controls (A) and those with ASD (B). The *dotted line* represents the linear regression fit.

reasons for the disparity between groups. Through the current literature and the results found here, adolescents with ASD present with greater motor control issues (35) and mechanical effort to perform activities of daily living along with a myriad of barriers to accessing opportunities for PA; issues that are not present for controls. As such, the large differences in gait mechanics–PA relationships found here highlight inherent differences between the study populations that necessitate a change in paradigm. Although it is common to assume that deviations from a control population are a negative attribute, we propose that the differences found here illustrate the necessity to analyze/treat each population separately. For instance, current literature indicates that children/adolescents with *and* without an ASD diagnosis do not meet PA guidelines (5,58); yet each group certainly has different barriers to engagement in PA and differences in gait mechanics (10). As such, we believe it would be inappropriate to assume that the complex biomechanical–PA relationships should be similar between those with and without ASD. In this instance, neurotypical

which should provide clarity.

There are limitations to note with this study. First, we examined gait mechanics in a closed, quiet environment, which may be notably different than what is available when engaging in PA. Second, the lack of speed differences in work is likely because of very similar self-selected speeds for both groups with the standardized 1.3 $m \cdot s^{-1}$. Future research should consider expanding the range of walking speeds and using a range of stride lengths/cadences. Lastly, we did not require participants to provide evidence of level of support required for their diagnosis. Future work should consider how these factors differ by level of support.

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