Movement smoothness during dynamic postural control to a static target differs between autistic and neurotypical children

For correspondence:
millerhl@umich.edu

Haylie L. Miller, Ph.D.[1,2]; Tylan N. Templin, M.S.[1,3]; Nicholas E. Fears, Ph.D.[1,2]; Gabriela M. Sherrod, M.S.[1,4]; Rita M. Patterson, Ph.D.[6]; & Nicoleta L. Bugnariu, PT, Ph.D., MBA[1,5]

[1]University of North Texas Health Science Center, School of Health Professions, 3500 Camp Bowie Blvd., Fort Worth, TX, 76109, USA
[2]University of Michigan, 830 N. University Ave., Ann Arbor, Michigan, 48170, USA
[3]Southwest Research Institute, 6220 Culebra Rd., San Antonio, TX, 78238, USA
[4]University of Alabama at Birmingham, 1720 University Blvd., Birmingham, AL, 35294, USA
[5]University of the Pacific, School of Health Sciences, 3200 Fifth Ave., Sacramento, CA, 95817, USA
[6]University of North Texas Health Science Center, Texas College of Osteopathic Medicine, 3500 Camp Bowie Blvd., Fort Worth, TX, 76109, USA

Please cite as: Miller, H. L., Templin, T., N., Fears, N. E., Sherrod, G. M., Patterson, R. M., & Bugnariu, N. L. (2021). Movement smoothness during dynamic postural control to a static target differs between autistic and neurotypical children. *SportRχiv*.

All authors have read and approved this version of the manuscript. This article was last modified on November 4th, 2021.

Authors Haylie Miller @*haylie_miller* and Nick Fears @*NickFears* can be reached on Twitter.

ABSTRACT

Autistic children and adults have known differences in motor performance, including postural instability and atypical gross motor control. Few studies have specifically tested dynamic postural control. This is the first study to quantify movement smoothness and its relationship to task performance during lateral dynamic postural control tasks in autism. We sought to test the hypothesis that autistic children would have less smooth movements to lateral static targets compared to neurotypical children, and that this difference would relate to specific movement strategies. We used camera-based motion-capture to measure spatiotemporal characteristics of lateral movement of a marker placed on the C7 vertebrae, and of markers comprising trunk and pelvis segments during a dynamic postural control task administered in an immersive virtual environment. We tested a sample of 15 autistic children and 11 age-matched neurotypical children. We quantified movement smoothness using dimensionless jerk cost. Autistic children exhibited more medial-lateral pelvic position range of motion compared to neurotypical children, and used a stepping strategy more often compared to neurotypical children. Autistic children also had higher jerk cost than neurotypical children for motion of the C7 marker. All participants had higher jerk cost for far targets than for near targets. Autistic children had longer trial durations than neurotypical children, and younger children had longer trial durations than older children across diagnostic groups. The stepping strategy observed more often in the autistic group likely contributed to jerk cost and reduced movement smoothness. This strategy is indicative of either an attempt to prevent an impending loss of balance, or an attempt to compensate for and recover from a loss of balance once it is detected. Implications of results are discussed, specifically with respect to anticipatory, feed-forward control of movement.

INTRODUCTION

Though not a current diagnostic feature of autism, motor differences have been noted both clinically and in research (for reviews, see Caçola et al., 2017; Heathcock et al., 2015; Lim et al., 2017; Ming et al., 2007). In some cases, autistic people meet criteria for a co-occurring diagnosis of Developmental Coordination Disorder (Green et al., 2009; Miller et al., 2021). Differences in perception of and responses to sensory input likely contribute to the core symptoms of ASD (Fulceri et al., 2019), including social communication (Cook, 2016;

Glazebrook, Elliott, & Szatmari, 2008; Leary & Hill, 1996), and may even rise to the level of a core feature or diagnostic specifier (Fournier et al., 2010; Leary & Hill, 1996; Whyatt & Craig, 2013).

Prior studies have identified motor differences in autistic compared to neurotypical participants during performance of gross motor tasks (Jansiewicz et al., 2006; Provost, Heimerl, & Lopez, 2007; Miller et al., 2021), postural stability tasks (Fournier et al., 2010; Miller et al., 2019; Minshew et al., 2004), and locomotion (Bugnariu et al., 2013; Hallett et al., 1993; Vernazza-Martin et al., 2005). However, the mechanisms underlying motor differences remain unclear. Imaging studies have also identified atypical neural activations in areas of the brain related to eye movement and visual processing (Brenner, Turner, & Müller, 2007; Luna et al., 2002; Takarae et al., 2007), and motor control (Mostofsky, Burgess, & Gidley Larson, 2007; Travers et al., 2017; Mosconi et al., 2015). It is possible that visuomotor integration mechanisms contribute to the broad range of motor differences observed in autism (Dowd et al., 2012; Miller et al., 2014; Williams, Whiten, & Singh, 2004; Mosconi et al., 2015; Wang et al., 2015).

A previous study established a relationship between smoothness of kinematic profiles and visual perception differences in autistic participants' goal directed reaching (Cook et al., 2013). Movement smoothness has previously been used as an index for motor performance in neurotypicality and neurodivergence (Ketcham et al., 2002; Platz et al., 1994; Rohrer et al., 2002; Teulings et al., 1997). Smoothness is frequently quantified as*jerk*–the derivative of acceleration with respect to time (Hogan & Sternad, 2009). Other measures (e.g., number of velocity peaks; Cirstea & Levin, 2000; Fetters & Todd, 1987) lack optimal sensitivity and robustness (Balasubramanian, Melendez-Calderon, & Burdet, 2012). The rationale for quantifying smoothness using jerk is rooted in the observation that many human movements are characterized by bell-shaped velocity curves (Cook, Blakemore, & Press, 2013; Flash & Hogan, 1985; Todorov & Jordan, 1998) and closely resemble trajectories predicted by minimum jerk and two-thirds power law equations (Flash & Hogan, 1985; Todorov & Jordan, 1998). Normalized jerk metrics have been used to show differences in smoothness of movements between neurotypical and neurodivergent populations (Hogan & Sternad, 2009). The advantage of normalizing jerk to a dimensionless value is that signals of different duration and amplitude can be compared (Hogan and Sternad 2009).

The aim of this study was to compare autistic and neurotypical children's dynamic postural control, quantified as the smoothness of goal-directed medial-lateral movements to a static target. Specifically, we assessed derivatives of time-series kinematic data, including

velocity, acceleration, and jerk. We hypothesized that smoothness would be significantly disrupted in autism, reflecting atypical motor control.

METHOD

The study protocol and informed consent/assent procedures were approved by the North Texas Regional Institutional Review Board. Informed consent/assent procedures were completed by participants and their guardian(s) as appropriate based on age and capacity.

Participants

Participants included 15 autistic children (Male=13, Female=2; M_{Age}=10.47 years, SD_{Age}=1.77 years) and 11 neurotypical children (Male=7, Female=4; M_{Age}=8.91 years, SD_{Age}=1.58 years).

Participants were recruited from schools, community organizations, clinics, and advocacy groups via face-to-face interactions, e-mail, and social media. Recruitment ads did not specifically solicit autistic participants with motor problems. Participants and their guardian(s) completed a developmental and medical history. Potential participants were excluded if they had a comorbid genetic or neurological disorder, seizure disorder, history of brain injury, structural brain abnormality, prior concussion with loss of consciousness, or coordination difficulties due to a general medical condition (e.g., cerebral palsy, hemiplegia, muscular dystrophy). Individuals taking medications known to significantly affect motor functioning (e.g., benzodiazepines, antipsychotics) were excluded, but given the comorbidity of attention disorders and prevalence of stimulant use in autism (DeFlippis & Wagner 2016), we did not exclude participants reporting stimulant use.

All autistic participants had a diagnosis assigned by a medical or educational professional based on the 4th or 5th edition of the Diagnostic and Statistical Manual of Mental Health Disorders (DSM; APA, 2000; 2013) and confirmed by the research team using the Autism Diagnostic Observation Schedule–Second Edition (ADOS-2; Lord et al., 2012). All participants had a non-verbal IQ score ≥ 70 confirmed by the research team using the Wechsler Abbreviated Scale of Intelligence–2nd edition (WASI-2; Wechsler, 2011). Participants in the neurotypical group had no prior history of developmental conditions and scored > 8 on the Social Communication Questionnaire (SCQ; Rutter, Bailey, & Lord, 2003), a conservative cutoff indicating no concern for autism.

Dynamic Postural Control Task

Participants performed a dynamic postural control task in an immersive virtual environment (see Miller, Bugnariu, Patterson, Wijayasinghe & Popa, 2017 for detailed description of apparatus). In this task, participants were instructed to move a user-controlled object (blue ball, 29.21 cm in diameter) into a static target area referred to as the *safe zone* (green box, 31.75 cm wide). The user-controlled object was controlled by medial-lateral movement of a marker placed on the participant's 7th cervical vertebrae (C7). The movement of the C7 marker was scaled by scaled by a factor of 5 when projected on the screen, such that a 1 cm change in the medial-lateral position of the C7 marker resulted in a 5 cm change of the user-controlled object.

Trials were classified as a "hit" if 70% of the user-controlled object was within the target area for 0.2 s. If 3 s elapsed without a successful hit, the safe zone disappeared. After each trial, the screen was then blank for 1s after which a central fixation cross appeared for 600 ms, prompting the participant to return to the starting position. The safe zones were located on either side of the participant (left or right) and at either 26.8 cm or 13.4 cm (far or near) away from the starting location (center). Four instances of each of these safe zone locations (a total of 16) were displayed in the virtual environment in a randomized order. After the last safe zone disappeared, the task ended.

Data Collection and Processing

28 reflective markers were placed on participants' head, trunk, pelvis, and feet. Kinematic data were acquired from an 18-camera motion capture system at 120 Hz using Cortex software (Motion Analysis Corporation, Santa Rosa, CA, USA). Kinematic data were filtered using a fourth order low-pass Butterworth filter with cutoff frequency of 6 Hz. The filtered medial-lateral C7 position data was extracted from Cortex. Frontal plane trunk angle (trunk lean) and medial-lateral pelvis center-of-mass (COM) position were calculated using Visual3D (C-Motion, Inc., Germantown, MD, USA). Velocity, acceleration, and jerk profiles were calculated in MATLAB (Mathworks Inc., Natick, MA, USA) using first, second, and third order three-point derivatives, respective of the position and joint angle data. Each derivative profile was filtered with the same fourth order low-pass Butterworth filter with cutoff frequency of 6 Hz. For trials when the safe zone appeared on the left, each data point (position, velocity, acceleration, and jerk profiles) was multiplied by -1, so that right- and left-side safe zones could be pooled for analysis.

Trial duration was calculated as elapsed time from safe zone onset to offset (either due to a "hit" or because the maximum 3s had elapsed). Each position, velocity, acceleration, and jerk profile was resampled to 101 points to represent 0-100% of the trial and grouped by diagnosis (autistic, neurotypical) and target distance (near, far).

Movement smoothness was quantified as the natural logarithm of the normalized and integrated squared jerk of an entire trial (Equation 1), as in previous work (Dixon et al., 2018; Gulde & Hermsdörfer, 2018). The start and endpoint of a trial were defined as the safe zone onset and offset, respectively.

$$log\ dimensionless\ jerk = -ln\left(\frac{(t_2-t_1)^5}{(x(t_2)-x(t_1))^2}\int_{t_1}^{t_2}\dddot{x}(t)^2dt\right) \quad (1)$$

Since trial duration was not held constant, and integrated squared jerk is sensitive to trial duration, it was important that this metric was normalized and converted to a dimensionless unit to make valid comparisons across trials (Hogan & Sternad, 2009). In addition, the natural logarithm brings the normalized and integrated squared jerk into the physiological range (Balasubramanian, Melendez-Calderon, & Burdet, 2012).

Data Analysis

Of the possible 416 trials available across the sample, 398 (95.7%) were included in analysis. Trials with durations shorter than 0.65 s were excluded because they were too short to represent volitional movement towards the target. These were either (1) trials in which the participant's starting position was already inside the safe zone, or (2) trials in which the participant was already moving toward the safe zone at the start of the trial.

Data were analyzed in a series of generalized mixed-effects models using the lme4 package in R (version 4.1). Generalized linear mixed-effects models (GLMM) using Gamma distribution with a log link were used to regress trunk and pelvic range of motion (ROM) and jerk cost onto group (autistic, neurotypical), distance (near, far), and age (in months at the time of data collection) with a random intercept by participant. A GLMM using a binomial distribution with a logit link was used to regress the number of steps taken during a movement onto the fixed effects of group, distance, and age with a random intercept by participant. Effects were considered significant if $p < 0.05$, and b weights are reported in log or log odds scale, respectively.

Results

Range of Motion

Generalized linear mixed-effects models using Gamma distribution with a log link were used to regress trunk leaning range of motion (ROM) and medial-lateral ROM of the pelvis position onto the fixed effects of group, distance, and age with a random intercept by participant. Figure 1 presents time-series kinematic data for the C7 marker, the trunk segment, and the pelvis segment.

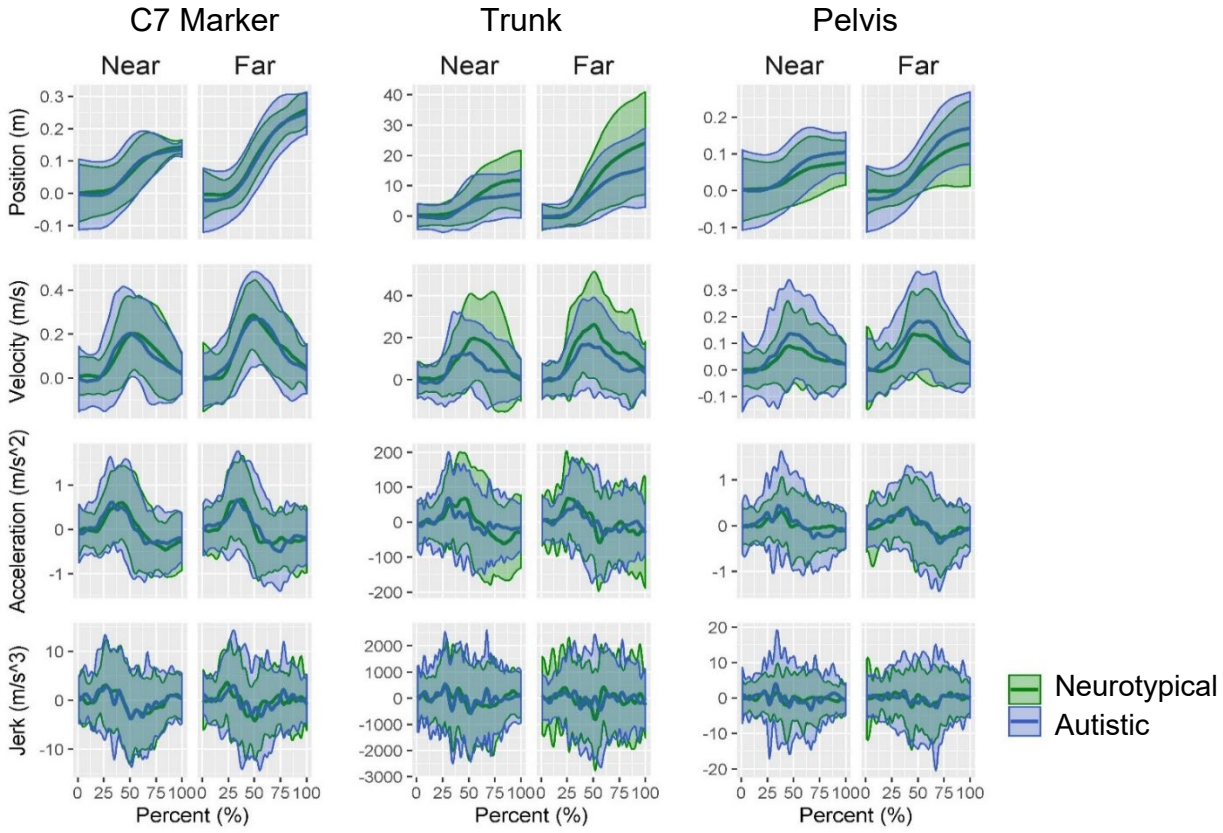

Figure 1. Spatiotemporal characteristics of autistic and neurotypical children's C7 marker, trunk segment, and pelvis segment movements to near and far targets from 0-100% of trial duration; mean (bold line) and standard deviation (lighter shading) of each derivative are displayed by group (autistic vs. neurotypical) and by distance to target (near vs. far).

Analysis of trunk leaning ROM yielded the expected main effect of distance (*Wald* χ^2_1=94.76, p<0.001), such that trunk ROM was higher for far targets (b=0.48, *SE*=0.05), but no main effect of group (*Wald* χ^2_1=0.31, p=0.58) or age (*Wald* χ^2_1=0.27, p=0.61). Analysis of medial-lateral ROM of the pelvis position yielded a main effect of group (*Wald* χ^2_1=8.49, p=0.004) such that pelvic ROM was greater for autistic children (b=0.72, *SE*=0.25), a main effect of age (*Wald* χ^2_1=3.88, p=0.049), such that older participants had lower pelvic ROM (b=-0.23, *SE*=0.12). There was also a main effect of distance (*Wald* χ^2_1=17.42, p<0.001), such that pelvic ROM was greater for far targets (b=0.35, *SE*=0.09). There were no significant interaction effects for trunk or pelvic ROM.

Movement Smoothness

C7 Marker.

The GLMM analysis for jerk cost of the C7 marker yielded main effects of group (*Wald* χ^2_1=4.02, p=0.045; Figure 2), such that autistic children had a higher jerk cost than neurotypical children (b=0.12, *SE*=0.06), and distance (*Wald* χ^2_1=6.51, p=0.011; Figure 2), such that movements to far targets were less smooth than movements to near targets (b=0.047, *SE*=0.02). There was not a main effect of age (*Wald* χ^2_1=1.89, p=0.17), nor were there any significant interaction effects.

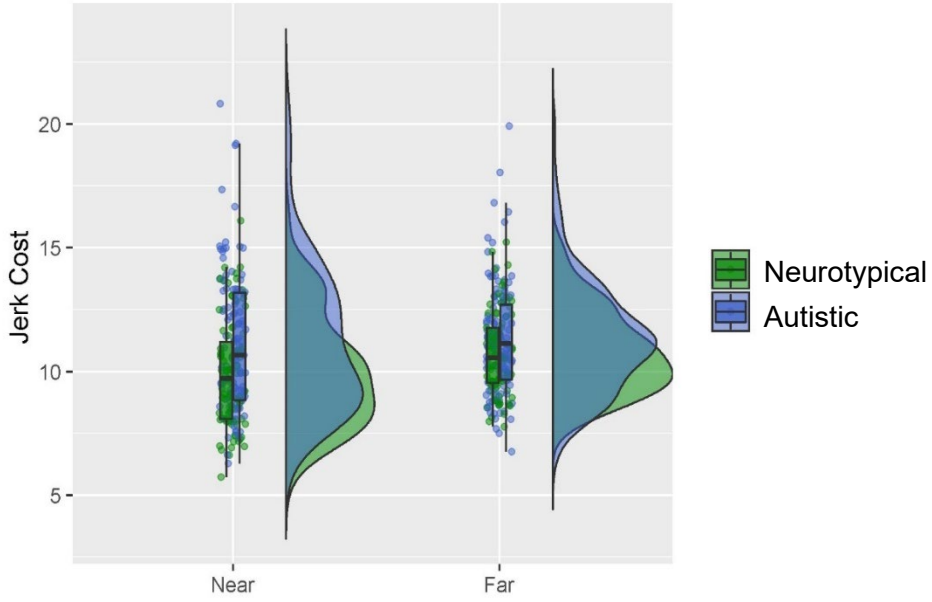

Figure 2. Jerk cost of autistic and neurotypical children's C7 marker movements to near and far targets.

Trunk Segment.

The GLMM analysis for jerk cost of the C7 marker yielded main effects of group (*Wald* χ^2_1=4.02, *p*=0.045; Figure 2), such that autistic children had a higher jerk cost than neurotypical children (*b*=0.12, *SE*=0.06), and distance (*Wald* χ^2_1=6.51, *p*=0.011; Figure 2), such that movements to far targets were less smooth than movements to near targets (*b*=0.047, *SE*=0.02). There was not a main effect of age (*Wald* χ^2_1=1.89, *p*=0.17), nor were there any significant interaction effects.

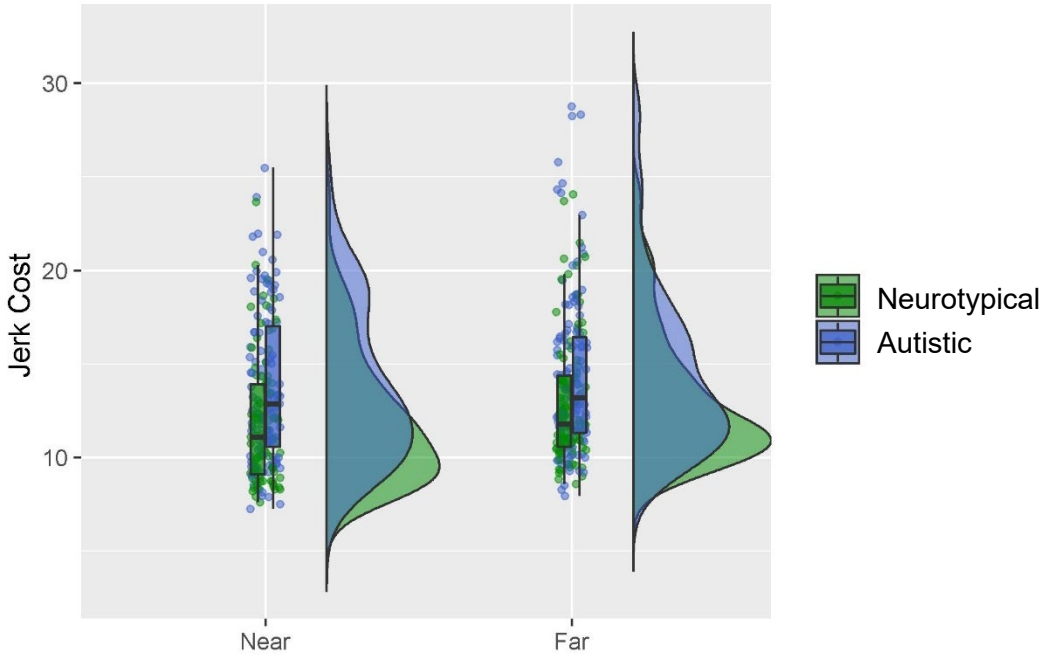

Figure 3. Jerk cost of autistic and neurotypical children's trunk segment movements to near and far targets.

Pelvis Segment.

The GLMM analysis for jerk cost of the pelvis segment yielded a main effect of distance (*Wald* χ^2_1=20.94, *p*<0.0001; Figure 4), such that movements to far targets were less smooth than movements to near targets (*b*=0.08, *SE*=0.02). There was not a main effect of age (*Wald* χ^2_1=2.33, *p*=0.13) or group (*Wald* χ^2_1=0.47, *p*=0.49), nor were there any significant interaction effects.

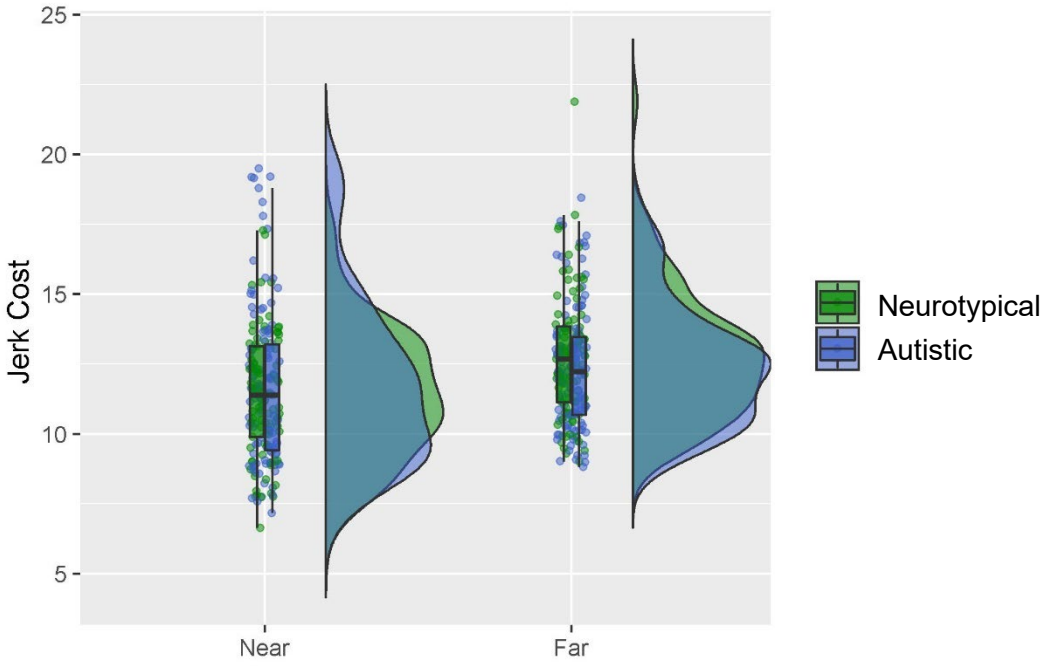

Figure 4. Jerk cost of autistic and neurotypical children's pelvis segment movements to near and far targets.

Trial Duration.

The GLMM analysis for trial duration yielded main effects of group (*Wald* χ^2_1=5.64, *p*=0.018; Figure 5), such that autistic children took more time to get to the safe zone than neurotypical children (*b*=0.15, *SE*=0.06), distance (*Wald* χ^2_1=69.0, *p*<0.0001; Figure 5), such that movements to far targets took more time than movements to near targets (*b*=0.24), and age (*Wald* χ^2_1=6.26, *p*=0.012; Figure 5), such that older participants reached the target more quickly than younger participants (*b*=-0.08, *SE*=0.03).

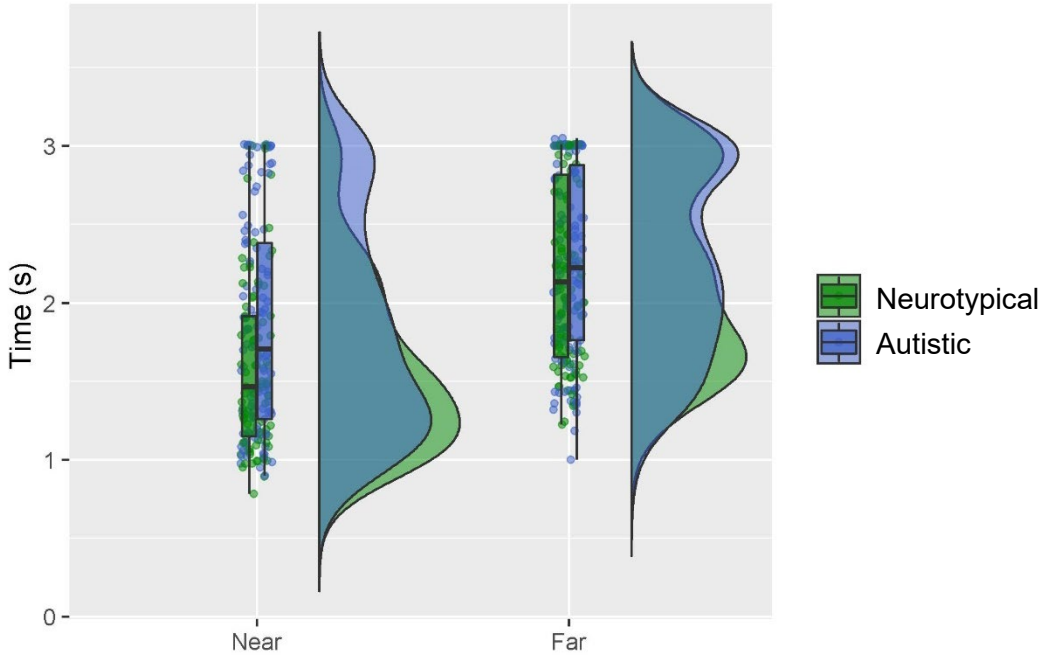

Figure 5. Trial duration for autistic and neurotypical children's movements to near and far targets.

Likelihood of Taking a Step.

The GLMM analysis for log odds of taking a step yielded a main effect of group (*Wald* χ^2_1=4.52 *p*=0.033; Figure 6), such that autistic children took a step during a trial more frequently relative to neurotypical children (*b*=2.40, *SE*=1.13), and distance (*Wald* χ^2_1=12.17, *p*=0.0005; Figure 6), such that participants were more likely to take a step towards a far target than a near target (*b*=1.07, *SE*=0.31). There was not a significant main effect of age (*Wald* χ^2_1=-1.05, *p*=0.059), nor were there any significant interaction effects.

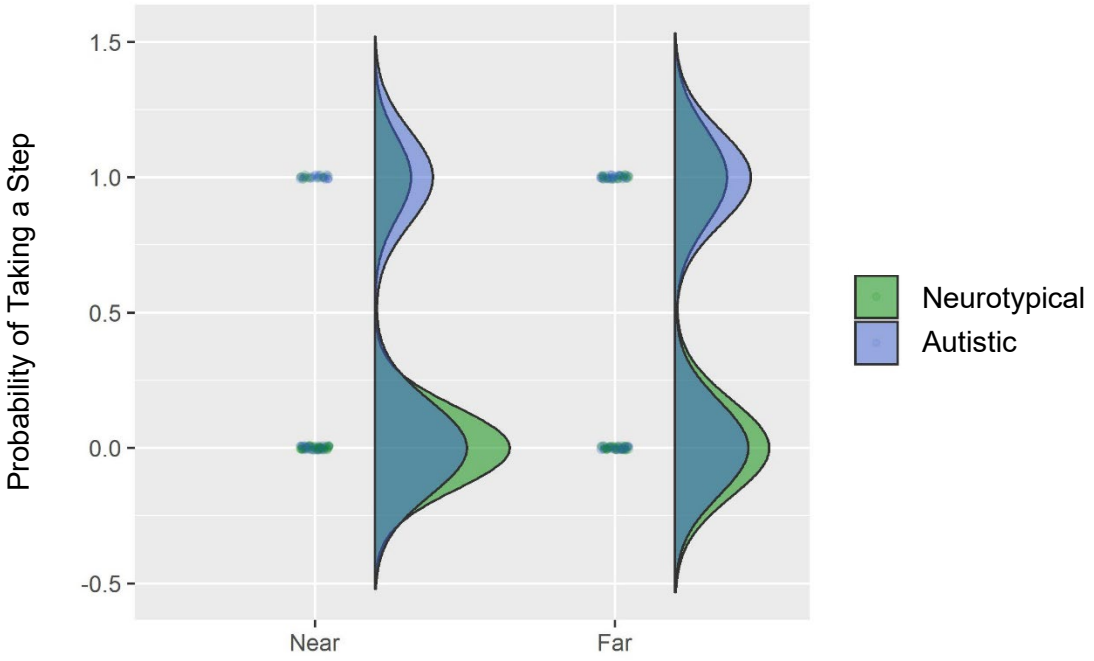

Figure 6. Results of a generalized linear mixed effects model using a binomial distribution with a logit link regressing the number of steps taken during a movement onto the fixed effects of group, distance, and age with a random intercept by participant showed that neurotypical children took fewer steps during the task compared to autistic children.

Discussion

This is the first study to quantify differences in movement smoothness between autistic and neurotypical children during goal-directed leaning. Consistent with r a prior study of gait smoothness (Nobile et al., 2011), autistic children in our sample exhibited higher jerk cost during goal-directed movement. Because participants were not given specific instructions about the mechanism of action for the user-controlled ball, they had to formulate their own movement strategy.

Participants generally adopted one of three strategies: 1) leaning at the trunk while keeping feet and lower body stationary, 2) moving the entire body by stepping, or 3) a mixture of both. For safe zones in far (versus near) locations, both groups exhibited jerkier movements, longer trial durations, and were more likely to take a step to maintain balance. This suggests that coordinating movements over a larger distance posed a greater challenge to both groups.

This is consistent with previous studies showing that movement duration is scaled by movement amplitude, and smoothness decreases as duration increases (Salmond, Davidson, & Charles, 2017; Ketcham et al., 2002).

Analysis of trunk leaning and medial-lateral position of the pelvis revealed that although trunk leaning ROM did not statistically differ between neurotypical and autistic children, medial-lateral pelvic ROM was significantly greater in the autistic group. Additionally, autistic children were more likely to take a step during a trial than neurotypical children. This demonstrates that autistic children relied more heavily on moving their entire body, rather than on isolating trunk movements, to reach the safe zone.

Leaning (versus stepping) to a lateral target requires coordination of fewer degrees of freedom, and may therefore be a more efficient strategy to produce smooth movements. However, increased trunk ROM places greater demand on core stabilizing muscles. Others have observed that autistic children have reduced core strength (Kern et al., 2011), which may explain heavier reliance on whole body movements (i.e., lateral stepping). Avoiding core muscle engagement may produce atypical and jerky movements as observed in the present study, or low-acceleration swaying movements when matching oscillating dynamic targets as we have previously reported (Miller et al., 2019). Examination of anticipatory and reactive muscle activity may help to explain why autistic individuals appear to adopt different strategies under varying task conditions.

Interestingly, despite higher overall jerk cost, jerk cost in intermediate joint and segment trajectories (trunk leaning and medial-lateral pelvis position) was not significantly higher for autistic children. This suggests that autistic children may exhibit only slightly jerkier movements of isolated segments, but when coordinating multiple joints to achieve a task, the jerkiness of the overall movement is exacerbated. Motor coordination is influenced by several factors including sensory processing, motor planning, and muscle activations. Previous studies demonstrated that some or all of these features may be different in autism (e.g., Cook et al., 2013; Dowd et al., 2012; Glazebrook et al., 2008; Luna et al., 2002; Mosconi et al., 2015; Mostofsky et al., 2007). Future work is needed to assess how autistic people acquire, process, and integrate sensory information to support planning, execution, and modification of goal-directed movements.

In our study, autistic children appeared to rely less on feed-forward information, often initiating movements and accelerating toward the target before sufficient visual intake and processing could occur. This may reflect anticipatory differences (Schmitz et al., 2003), or a learned response to a lifetime of experiences with atypical visual processing (Sharer et al.,

2015) in turn forcing over-reliance on feed-back information after movement initiation. This approach is associated with reduced movement smoothness and efficiency (Liu & Todorov, 2007), consistent with our results. Over-reliance on feed-back control (as opposed to stochastic optimal control) is also a more effortful, on-line processing approach (Todorov & Jordan, 2002), potentially contributing to the longer trial durations we observed.

Conclusion

While movement smoothness has not previously been a key variable of interest in autism research, our results demonstrate that it is related to both the motor strategy selected for a given task, and the efficiency with which that task is performed. Accuracy, efficiency, and flexibility in dynamic postural control are necessary for functional mobility and mitigation of fall risk. They are also important determinants of how effortful and fatiguing a motor task is, and thus relate to quality of life. It is important to characterize the mechanisms underlying postural control and the impact of movement smoothness on functional mobility and fall risk in autism. In doing so, we will be better equipped to develop accommodations and interventions that support autistic individuals' ability to move more efficiently, safely, and comfortably

Contributions

Contributed to conception and design: HLM, RMP, NLB
Contributed to acquisition of data: HLM, GMS
Contributed to analysis and interpretation of data: TNT, HLM, NEF, RMP, NLB
Drafted and/or revised the article: HLM, TNT, NEF
Approved the submitted version for publication: HLM, TNT, NEF, GMS, RMP, NLB

Acknowledgements

We thank all of the children, adults, and caregivers who participated in this research. We appreciate the community feedback we received in developing the virtual reality task, and we agree that it would have been better with sharks.

Funding information

This work was funded in part by grants from the National Science Foundation [SMA-1514495; NRI-1208621; CPS-1035913]; the National Institutes of Health/National Center for Translational Sciences [KL2-TR001103]; and the National Institutes of Health/National Institute of Mental Health [K01-MH107774].

Data and Supplementary Material Accessibility

The data for this paper are currently in the process of being transferred from one university to another. As there are ongoing discussions about the rights and obligations for this dataset, it cannot be shared at this time.

REFERENCES

American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders* (4th ed., Text Revision). Washington, DC: American Psychiatric Publishing.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Arlington, VA: American Psychiatric Publishing.

Balasubramanian, S., Melendez-Calderon, A., & Burdet, E. 2012. A robust and sensitive metric for quantifying movement smoothness. *IEEE Transactions on Bio-Medical Engineering* 59(8):2126–36. https://doi.org/10.1109/TBME.2011.2179545

Brenner, L. A., Turner, K. C., & Müller, R. A. 2007. Eye movement and visual search: Are there elementary abnormalities in autism? *Journal of Autism and Developmental Disorders* 37(7):1289–1309. https://doi.org/10.1007/s10803-006-0277-9

Bugnariu, N., Young, C., Rockenbach, K., Patterson, R. M. ,Garver, C., Ranatunga, I., Beltran, M., Torres-Arenas, N., & Popa, D. O. 2013. Human-robot interaction as a tool to evaluate and quantify imitative motor behavior in children with Autism Spectrum Disorders. Pp. 57–62 in *2013 International Conference on Virtual Rehabilitation, ICVR 2013*. IEEE Computer Society. https://doi.org/10.1109/ICVR.2013.6662088

Caçola, P., Miller, H. L., & Williamson, P. O. (2017). Behavioral comparisons in Autism Spectrum Disorder and Developmental Coordination Disorder: A systematic literature review. *Research in Autism Spectrum Disorders*, *38*, 6–18. https://doi.org/10.1016/j.rasd.2017.03.004

Cai, L. L., Fong, A. J., Otoshi, C. K., Liang, Y., Burdick, J. W., Roy, R. R., & Edgerton, V. R. (2006). Implications of assist-as-needed robotic step training after a complete spinal cord injury on intrinsic strategies of motor learning. *Journal of Neuroscience*, *26*(41), 10564–10568. https://doi.org/10.1523/JNEUROSCI.2266-06.2006

Cirstea, M. C., & Levin, M. F. 2000. Compensatory strategies for reaching in stroke. *Brain* 123(5):940–53. https://doi.org/10.1093/brain/123.5.940

Cook, J. 2016. From movement kinematics to social cognition: The case of autism. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 371(1693). https://doi.org/10.1098/rstb.2015.0372

Cook, J. L., Blakemore, S. J., & Press, C. 2013. Atypical basic movement kinematics in Autism Spectrum Conditions. *Brain* 136(9):2816–24. https://doi.org/10.1093/brain/awt208

Dewey, D., Cantell, M., & Crawford, S. J. 2007. Motor and gestural performance in children with Autism Spectrum Disorders, Developmental Coordination Disorder, and/or Attention Deficit Hyperactivity Disorder. *Journal of the International Neuropsychological Society : JINS* 13(2):246–56. https://doi.org/10.1017/S1355617707070270

Dinstein, I., Heeger, D. J., & Behrmann, M. 2015. Neural variability: Friend or foe? *Trends in Cognitive Sciences*, Vol. 19, pp. 322–328. https://doi.org/10.1016/j.tics.2015.04.005

Dixon, P. C., Stirling, L., Xu, X., Chang, C. C., Dennerlein, J. T., & Schiffman, J. M. (2018). Aging may negatively impact movement smoothness during stair negotiation. *Human Movement Science*, *60*, 78–86. https://doi.org/10.1016/j.humov.2018.05.008

Dowd, A. M., McGinley, J. L., Taffe, J. R., & Rinehart, N. J. 2012. Do planning and visual integration difficulties underpin motor dysfunction in autism? A kinematic study of young children with autism. *Journal of Autism and Developmental Disorders* 42(8):1539–48. https://doi.org/10.1007/s10803-011-1385-8

Dziuk, M., Gidle, A., Larson, J. C., Apostu, A., Mahone, E. M., Denckla, M. B., & Mostofsky, S. H. 2007. Dyspraxia in autism: association with motor, social, and communicative deficits. *Developmental Medicine and Child Neurology* 49(10):734–39. https://doi.org/10.1111/j.1469-8749.2007.00734.x

Fetters, L., & Todd, J. 1987. Quantitative assessment of infant reaching movements. *Journal of Motor Behavior* 19(2):147–66. https://doi.org/10.1080/00222895.1987.10735405

Flash, T., & Hogan, N. 1985. The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience* 5(7):1688–1703. https://doi.org/10.1523/JNEUROSCI.05-07-01688.1985

Fournier, K. A., Kimberg, C. I., Radonovich, K. J., Tillman, M. J., Chow, J. W., Lewis, M. H., Bodfish, J. W., & Hass, C. J. 2010. Decreased static and dynamic postural control in children with Autism Spectrum Disorders. *Gait and Posture* 32(1):6–9. https://doi.org/10.1016/j.gaitpost.2010.02.007

Fulceri, F., Grossi, E., Contaldo, A., Narzisi, A., Apicella, F., Parrini, I., Tancredi, R., Calderoni, S., & Muratori, F. 2019. Motor skills as moderators of core symptoms in autism spectrum disorders: Preliminary data from an exploratory analysis with artificial neural networks. *Frontiers in Psychology, 09 January 2019.* https://doi.org/10.3389/fpsyg.2018.02683

Glazebrook, C. M., Elliott, D., & Szatmari, P. 2008. How do individuals with autism plan their movements? *Journal of Autism and Developmental Disorders* 38(1):114–26. https:/doi.org/10.1007/s10803-007-0369-1

Green, D., Charman, T., Pickles, A., Chandler, S., Loucas, T., Simonoff, E., & Baird, G. (2009). Impairment in movement skills of children with autistic spectrum disorders. *Developmental Medicine and Child Neurology*, *51*(4), 311–316. https://doi.org/10.1111/j.1469-8749.2008.03242.x

Gulde, P., & Hermsdörfer, J. 2018. Smoothness metrics in complex movement tasks. *Frontiers in Neurology*, *9*(SEP). https://doi.org/10.3389/fneur.2018.00615

Hallett, M., Lebiedowska, M. K., Thomas, S. L., Stanhope, S. J., Denckla, M. B., & Rumsey, L. 1993. Locomotion of autistic adults. *Archives of Neurology* 50(12):1304–8. https://doi.org/10.1001/archneur.1993.00540120019007

Harbourne, R. T., & Stergiou, N. (2009). Movement variability and the use of nonlinear tools: Principles to guide physical therapist practice. *Physical Therapy*, *89*(3), 267–282. https://doi.org/10.2522/ptj.20080130

Heathcock, J. C., Tanner, K., Robson, D., Young, R., & Lane, A. E. (2015). Retrospective analysis of motor development in infants at high and low risk for autism spectrum disorder. *American Journal of Occupational Therapy*, *69*(5), 6905185070. https://doi.org/10.5014/ajot.2015.017525

Hedgecock, J. B., Dannemiller, L. A., Shui, A. M., Rapport, M. J., & Katz, T. (2018). Associations of gross motor delay, behavior, and quality of life in young children with Autism Spectrum Disorder. *Physical Therapy, 98*. https://doi.org/10.1093/ptj/pzy006

Hogan, N., & Sternad, D. (2009). Sensitivity of smoothness measures to movement duration, amplitude, and arrests. *Journal of Motor Behavior*, *41*(6), 529–534. https://doi.org/10.3200/35-09-004-RC

Jansiewicz, E. M., Goldberg, M. C., Newschaffer, C., Denckla, M., Landa, R., & Mostofsky, S. H.. 2006. Motor signs distinguish children with high functioning autism and Asperger's Syndrome from controls. *Journal of Autism and Developmental Disorders* 36(5):613–21. https://doi.org/10.1007/s10803-006-0109-y

Kawato, M., & Wolpert, D. (1998). Internal models for motor control. *Novartis Foundation Symposium*, (218), 291–307.

Kern, J. K., Geier, D. A., Adams, J. B., Troutman, M. R., Davis, G., King, P. G.,...& Geier, M. R. (2011). Autism severity and muscle strength: A correlation analysis. *Research in Autism Spectrum Disorders, 5*(3), 1011-5. https://doi.org/10.1016/j.rasd.2010.11.002

Ketcham, C. J., Seidler, R. D., Van Gemmert, A. W. A., & Stelmach, G. E. 2002. Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences* 57(1). https://doi.org/10.1093/geronb/57.1.P54

Leary, M. R., & and Hill, D. A. 1996. Moving on: Autism and movement disturbance. *Mental Retardation* 34(1):39–53.

Lim, Y. H., Partridge, K., Girdler, S., & Morris, S. L. (2017). Standing postural control in individuals with Autism Spectrum Disorder: Systematic review and meta-analysis. *Journal of Autism and Developmental Disorders*, *47*(7), 2238–2253. https://doi.org/10.1007/s10803-017-3144-y

Liu, D., & Todorov, E., Evidence for the flexible sensorimotor strategies predicted by optimal feedback control. *Journal of Neuroscience, 27*(35), 9354-9368. https://doi.org/10.1523/JNEUROSCI.1110-06.2007

Lord, C., Rutter, M., DiLavore, P. C., Risi, S., Gotham, K., & Bishop, S. 2012. *Autism Diagnostic Observation Schedule, Second Edition (ADOS-2) Manual (Part I): Modules 1–4.* Western Psychological Services, Torrance, CA.

Luna, B., Minshew, N. J., Garver, K. E., Lazar, N. A., Thulborn, K. R., Eddy, W. F., & Sweeney, J. A. 2002. Neocortical system abnormalities in autism: An fMRI study of spatial working memory. *Neurology* 59(6):834–40. https://doi.org/10.1212/WNL.59.6.834

Miller, H. L., Bugnariu, N., Patterson, R. M., Wijayasinghe, I., & Popa, D. O. 2017. Development of a novel visuomotor integration paradigm by integrating a virtual environment with mobile eye-tracking and motion-capture systems. *International Conference on Virtual Rehabilitation, ICVR* 2017-June. https://doi.org/10.1109/ICVR.2017.8007481

Miller, H. L., Sherrod, G., Mauk, J., Fears, N., & Caçola, P. (2021). Shared features or co-occurrence? Evaluating symptoms of Developmental Coordination Disorder in children and adolescents with Autism Spectrum Disorder. *Journal of Autism & Developmental Disorders,* ePub ahead of print. https://doi.org/10.1007/s10803-020-04766-z.

Miller, H. L., Caçola, P. M., Sherrod, G. M., Patterson, R. M., & Bugnariu, N. L. 2019. Children with Autism Spectrum Disorder, Developmental Coordination Disorder, and typical development differ in characteristics of dynamic postural control: A preliminary study. *Gait and Posture* 67:9–11. https://doi.org/10.1016/j.gaitpost.2018.08.038

Miller, M., Chukoskie, L., Zinni, M., Townsend, J., & Trauner, D. 2014. Dyspraxia, motor function and visual-motor integration in autism. *Behavior & Brain Research, 269*, 95-102. https://doi.org/10.1016/j.bbr.2014.04.011

Ming, X., Brimacombe, M., & Wagner, G. C. 2007. Prevalence of motor impairment in Autism Spectrum Disorders. *Brain & Development* 29(9):565–70. https://doi.org/10.1016/j.braindev.2007.03.002

Minshew, N. J., Sung, K., Jones, B. J., & Furman, J. 2004. Underdevelopment of the postural control system in autism. *Neurology* 63(Ns 33355):2056–61. https://doi.org/10.1212/01.WNL.0000145771.98657.62

Mosconi, M. W., Mohanty, S., Greene, R. K., Cook, E. H., Vaillancourt, D. E., & Sweeney, J. A. (2015). Feedforward and feedback motor control abnormalities implicate cerebellar dysfunctions in autism spectrum disorder. *Journal of Neuroscience*, *35*(5), 2015–2025. https://doi.org/10.1523/JNEUROSCI.2731-14.2015

Mostofsky, S. H., Burgess, M. P., & Gidley Larson, J. C. 2007. Increased motor cortex white matter volume predicts motor impairment in autism. *Brain : A Journal of Neurology* 130(Pt 8):2117–22. https://doi.org/10.1093/brain/awm129

Mostofsky, S. H., Dubey, P., Jerath, V. K., Jansiewicz, E. M., Goldberg, M. C., & Denckla, M. B. 2006. Developmental dyspraxia is not limited to imitation in children with Autism Spectrum Disorders. *Journal of the International Neuropsychological Society* 12(3):314–26. https:/doi.org/10.1017/S1355617706060437

Nobile, M., Perego, P., Piccinini, L., Mani, E., Rossi, A., Bellina, M., & Molteni, M. 2011. Further evidence of complex motor dysfunction in drug naïve children with autism using automatic motion analysis of gait. *Autism, 15*(3):263-283. https://doi.org/10.1177%2F1362361309356929

Platz, T., Denzler, P., Kaden, B. & Mauritz, K. H. 1994. Motor learning after recovery from hemiparesis. *Neuropsychologia* 32(10):1209–23. https://doi.org/10.1016/0028-3932(94)90103-1

Provost, B., Heimerl, S. & Lopez, B. R. 2007. Levels of gross and fine motor development in young children with Autism Spectrum Disorder. *Physical and Occupational Therapy in Pediatrics* 27(3):21–36. https://doi.org/10.1080/J006v27n03_03

Rohrer, B., Fasoli, S., Krebs, H. I., Hughes, R., Volpe, B., Frontera, W. R., Stein, J., & Hogan, N. 2002. Movement smoothness changes during stroke recovery. *Journal of Neuroscience* 22(18):8297–8304. https://doi.org/10.1523/JNEUROSCI.22-18-08297.2002

Rutter, M., Bailey, A., & Lord, C. 2003. *Social Communication Questionnaire.* Western Psychological Services, Torrence, CA.

Salmond, L. H., Davidson, A. D., & Charles, S. K. 2017. Proximal-distal differences in movement smoothness reflect differences in biomechanics. *Journal of Neurophysiology, 117*(3):1239-1257. https://doi.org/10.1152/jn.00712.2015

Schmitz, C., Martineau, J., Barthelemey, C., & Assaiante, C.2003. Motor control and children with autism: a deficit of anticipatory function? *Neuroscience Letters, 348*(1), 17-20. https://doi.org/10.1016/S0304-3940(03)00644-X

Sharer E, Crocetti D, Muschelli J, et al. Neural correlates of visuomotor learning in autism. *Journal of Child Neurology, 30*(14):1877-1886. https://doi.org/10.1177%2F0883073815600869

Takarae, Y., Minshew, N. J., Luna, B., & Sweeney, J. A.. 2007. Atypical involvement of frontostriatal systems during sensorimotor control in autism. *Psychiatry Research* 156(2):117–27. https://doi.org/10.1016/j.pscychresns.2007.03.008

Teulings, H. L., Contreras-Vidal, J. L., Stelmach, G. E., & Adler, C. H. 1997. Parkinsonism reduces coordination of fingers, wrist, and arm in fine motor control. *Experimental Neurology* 146(1):159–70. https://doi.org/10.1006/exnr.1997.6507

Todorov, E. & Jordan, M. I. 1998. Smoothness maximization along a predefined path accurately predicts the speed profiles of complex arm movements. *Journal of Neurophysiology* 80(2):696–714. https://doi.org/10.1152/jn.1998.80.2.696

Todorov, E., & Jordan, M. I. 2002. Optimal feedback control as a theory of motor coordination. Nature Neuroscience, 5(11), 1226-1235.Stergiou, N., Harbourne, R. T., & Cavanaugh, J. T. 2006. Optimal movement variability. *Journal of Neurologic Physical Therapy*, *30*(3), 120–129. https://doi.org/10.1038/nn963

Torres, E. B., & Denisova, K. (2016). Motor noise is rich signal in autism research and pharmacological treatments. *OPEN*, *Nature Publishing Group*. https://doi.org/10.1038/srep37422

Travers, B. G., Bigler, E. D., Duffield, T. C., Prigge, M. D. B., Froehlich, A. L., Lange, N., Lainhart, J. E. (2017). Longitudinal development of manual motor ability in autism spectrum disorder

from childhood to mid-adulthood relates to adaptive daily living skills. *Developmental Science*, *20*(4), e12401. https://doi.org/10.1111/desc.12401

Vernazza-Martin, S., N. Martin, A. Vernazza, A. Lepellec-Muller, M. Rufo, J. Massion, and C. Assaiante. 2005. Goal directed locomotion and balance control in autistic children. *Journal of Autism and Developmental Disorders* 35(1):91–102. http://doi.org/10.1007/s10803-004-1037-3

Wang, Z., Magnon, G. C., White, S. P., Greene, R. K., Vaillancourt, D. E., & Mosconi, M. W. (2015). Individuals with autism spectrum disorder show abnormalities during initial and subsequent phases of precision gripping. *Journal of Neurophysiology*, *113*(7), 1989–2001. https://doi.org/10.1152/jn.00661.2014

Whyatt, C., & Craig, C. (2013). Sensory-motor problems in autism. *Frontiers in Integrative Neuroscience*, 7 (2013), p. 51 https://doi.org/10.3389/fnint.2013.00051

Williams, J. H. G., Whiten, A., & Singh, T. 2004. A systematic review of action imitation in Autistic Spectrum Disorder. *Journal of Autism and Developmental Disorders* 34(3):285–99. https://doi.org/10.1023/B:JADD.0000029551.56735.3a

APPENDIX

Participant Instructions & Feedback

Participants heard and saw the following instructions with embedded visual examples of the user-controlled object and the safe zone on the screen:

> *"In this game, you will see a blue ball on the screen. This is your ball. When you move your body, your ball will move too. This is a green safe zone. Move your body to get your ball in the green safe zone. Move as fast as you can! Sometimes, the safe zone is in a different place. Try to stay in the safe zone!"*

Participants were not given specific information about the control mechanism of the user-controlled object, the locations of the safe zones, or hit criteria. After a successful hit, virtual fireworks and a sound signaled success. If 3 s elapsed without a successful hit, the safe zone disappeared and a thumping sound signaled failure.

AUTHOR NOTE

Out of respect for preferences expressed by many autistic self-advocates in our studies and in the community, we have chosen to use identity-first (rather than person-first) language throughout this manuscript. In doing so, it is not our intention to diminish or invalidate the preferences or perspectives of those who prefer person-first language. We continue to welcome feedback on ways that we can effectively partner with the autistic community to advocate for respect, acceptance, inclusion, and representation in research.