Motor differences in autism during a human-robot imitative gesturing task

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ABSTRACT

Difficulty with imitative gesturing is frequently observed as a clinical feature of autism. Current practices for assessment of imitative gesturing ability–behavioral observation and parent report–do not allow precise measurement of specific components of imitative gesturing performance, instead relying on subjective judgments. Advances in technology allow researchers to objectively quantify the nature of these movement differences, and to use less

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socially stressful interaction partners (e.g., robots). In this study, we aimed to quantify differences in imitative gesturing between autism and neurotypical development during human-robot interaction. Thirty-five autistic (*n* = 19) and neurotypical (*n* = 16) participants imitated social gestures of an interactive robot (e.g., wave). The movements of the participants and the robot were recorded using an infrared motion-capture system with reflective markers on corresponding head and body locations. We used dynamic time warping to quantify the degree to which the participant's and robot's movement were aligned across the movement cycle. Results revealed differences between autism and neurotypical participants in imitative accuracy, primarily in the movements requiring unilateral extension of the arm. Imitative gesturing is a building block to later development of social-communication skills; difficulty with reproduction and functional use of gestures may negatively impact social engagement, and in turn, learning opportunities. It is important to understand the underlying motor control and sensorimotor integration mechanisms that support imitative gesturing in ASD in order to identify appropriate intervention targets.

INTRODUCTION

Prior to the development of language, imitation and nonverbal communicative gesturing play a crucial role in early learning development (Meltzoff & Moore, 1983). Copying the movements of others is a mechanism by which children hone a broad range of functional and social skills requiring fine- and gross-motor competency (for review, see Jones, 2009). Imitative gesturing also facilitates successful development of language (Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979) and social interaction (Iacoboni, 2005).

Substantial evidence indicates that autistic individuals have specific difficulties with reproducing an observed motor action (for reviews, see Smith & Bryson, 1994; Rogers, 1999; Williams, Whiten, & Singh, 2004) as well as difficulty inferring intent from gestures (Bhat, Landa, & Galloway, 2011). Specifically, differences in imitative gesturing is often observed (de Marchena et al., 2018; Ellawadi & Weismer, 2014; McAuliffe et al., 2017; Rogers, Bennetto, McEvoy, & Pennington, 1996; Mostofsky et al., 2006; Smith & Bryson, 2007; Young et al., 2011), and distinguishes autism from other developmental, movement, and attention disorders (Rogers, Hepburn, Stackhouse, & Wehner, 2003; Minshew, Sung, Jones, & Furman, 2004; Dewey, Cantell, & Crawford, 2007; MacNeil & Mostofsky, 2012; Veness et al., 2012). Recently, de Marchena and colleagues (2018) found that autistic adults demonstrated both pragmatic and motoric differences in co-speech gestures during a conversational task.

These differences may stem from atypical functioning of the mirror neuron system (MNS) (Martineau, Andersson, Barthelemy, Cottier, & Destrieux, 2010; Williams, Whiten, Suddendorf, & Perrett, 2001), and/or from differences in general motor planning skills (Green et al., 2009; Gonzalez, Glazebrook, Studenka, & Lyons, 2013; Hughes, 1996; Miller et al., 2021; Scharoun & Bryden, 2016).

However, to date, few studies have characterized gestural differences in autism using precisely-quantifiable methods (e.g., Anzulewicz, Sobota, & Delafield-Butt, 2016; Tunçgenç et al., 2021). Current practice for assessing the quality of imitation and gesturing relies heavily on caregiver report (e.g., Autism Diagnostic Interview–Revised) and behavioral observation or video coding (e.g., Watson et al., 2014). Fundamental motor coordination problems may underlie difficulties with higher-order, more complex motor behaviors such as gesturing. Apart from the body of mirror neuron work (for review, see Vivanti & Rogers, 2014), little is known about the specific mechanisms that contribute to imitative gesturing differences between autistic and neurotypical development.

Imitation of Non-Human Actors

A frequent goal of social skills interventions in autism is the development of appropriate gestures and nonverbal means of communication (e.g., Ingersoll, Lewis, & Kroman, 2007). At present, most intervention approaches involve direct interaction between a autistic person and a human actor. Given the difficulty with social interaction inherent to autism, it follows that these settings may increase anxiety for patients and/or limit their ability to fully engage in the intervention.

Alternatives to human actors have been explored, including studies using avatars (e.g., Kandalaft, Didehbani, Krawczyk, Allen, & Chapman, 2013; Hopkins et al., 2011) and robots (Boucenna, Cohen, Meltzoff, Gaussier, & Chetouani, 2016; So et al., 2017; Srinivasan, Eigsti, Neelly, & Bhat, 2016; Warren et al., 2015a/b; Zheng et al., 2016). Recently, significant advancements have been made in the field of humanoid robots, most notably in their ability to accurately reproduce and imitate human movements (for reviews, see Borghi & Cangelosi, 2014; Cangelosi, Schlesinger, & Smith, 2015). These advancements opened the possibility of human-robot interactions in which robots “teach” movements to be imitated by humans. A small number of studies specifically highlight the potential of robots to serve as dynamic tools for teaching imitative gesturing through engagement with autistic individuals (e.g., So et al., 2017; Warren et al., 2015a).

Benefits of using robots to investigate gesturing and imitation are myriad: they can be programmed to produce lifelike movements with specific spatial or temporal characteristics, they repeat movements more reliably than humans, and they are engaging and nonthreatening for autistic children (Bekele, Crittendon, Swanson, Sarkar, & Warren, 2013). Indeed, Zheng et al. (2016) and Srinivasan et al. (2016) found that a robot therapist drew greater attention than a human therapist. However, more quantitative and controlled studies are needed to determine the utility of robots for autistic individuals.

Assessing Accuracy of Imitated Movement

Studies have attempted to quantify the accuracy of imitated movements by autistic individuals (Salowitz et al., 2013; Rogers et al., 2003; Toth, Munson, Meltzoff, & Dawson, 2006; Tunçgenç et al., 2021; Wild, Poliakoff, Jerrison, & Gowen, 2012). For example, Salowitz and colleagues (2013) asked autistic children to watch a video demonstrating 52 hand and arm gestures. After each gesture was shown on the screen, the children were given the opportunity to copy the movement they had just observed. Results showed that the hand shape and orientation of autistic imitations were less accurate than those of neurotypical controls. Autistic children also used an inaccurate number of arm or hand movements to complete a given gesture.

Observational behavioral coding is commonly used to measure imitation accuracy in autism, either by watching subjects in real-time or reviewing videotaped subject performances (e.g., Rogers et al., 2003; Toth et al., 2006; Salowitz et al., 2013; Romero et al., 2018). These studies require time-consuming review of subject behavior and multiple behavioral coders to ensure high inter-rater reliability and minimize human error inherent to this method.

In contrast, few groups (e.g., Wild et al., 2012; Tunçgenç et al., 2021) have used direct measurement of biomechanical or kinematic data to quantify the degree to which an imitative gesture matches positional elements of a target movement. Both temporal and positional elements of a gesture are used to convey functional meaning. If a gesture is temporally-atypical (e.g., too fast or slow, jerky), the movement can still be understood as a bid for attention, though the emotional valence or level of urgency may be less clear (Koul et al., 2019). In contrast, if a person attempts to wave but executes positional aspects of the movement atypically (e.g., trajectory, number of path components used in the movement, body or limb posture), an onlooker may not understand the core intent of the gesture.

Dynamic Time Warping (DTW; Berndt & Clifford, 1994) offers a mathematical solution for examining the positional accuracy of a gesture, independent of differences between the actor and the observer in temporal elements of the movement. Upper extremity movement is temporally variable and complex (Rab, Petuskey, & Bagley, 2002). Particularly in the case of imitation, the actor's and observer's movements will always be asynchronous due to the time required to engage in visuomotor processing of the observed action and motor planning of a response. For two movements that vary even slightly in speed, analysis of point-by-point positional matching across the timeseries will not accurately reflect a person's functional performance of an imitative movement. Phasic analysis, as commonly performed in studies of gait, also carries inherent limitations given difficulties in setting thresholds for onset and offset of each phase (Simon, 2004). Instead, in the present study, we have employed the DTW approach to minimize the effects temporal asynchrony and focus our analysis on positional matching across the full cycle of a movement (hand wave) from initiation to completion.

Objectives and Hypotheses

We aimed to quantify imitative accuracy in individual with ASD compared to TD individuals during a human-robot imitation task. To achieve this objective, we used a paradigm developed to measure the kinematic accuracy of gestural imitation between an individual with ASD and a humanoid robot (Bugnariu et al., 2013; Ranatunga et al., 2013; Ranatunga et al., 2012; Wijayasinghe et al., 2016). We used a robot as the interaction partner to improve participants attention to the motor task (Bekele et al., 2013) and potentially reduce the influence of social demands on participants (Wang & Quadflieg, 2015). For this reason, we were able to focus on the kinematic aspects of imitation rather than aspects dependent on the participant's ability to infer meaning or engage in ways that were specifically social in nature. The use of a robot interaction partner also enabled us to collect multiple trials of the exact same movement for each participant, without introducing variability inherent to a human actor's execution of a gesture. This approach supported our goal of characterizing the use of upper extremity coordination and visuomotor integration in autism to accurately perceive and reproduce a movement.

We hypothesized that autistic individuals would produce less accurate imitations of a robot's waving movement, reflected in higher DTW values, than their neurotypical counterparts. Little prior work exists specifically examining gestural imitation differences between autistic and neurotypical individuals, particularly using analytical approaches that allow comparisons independent of temporal constraints. Therefore, this study advances our understanding of the nature and magnitude of effect sizes observed between groups in this novel approach to analysis.

METHOD

Participants

We recruited and enrolled 19 autistic and 16 neurotypical individuals (see Table 1). Participants were recruited through local service providers, community organizations, schools, and clinics. Participants in the autism group had a prior diagnosis of Autism Spectrum Disorder based on clinical criteria specified by the 4th or 5th edition of the Diagnostic and Statistical Manual of Mental Health Disorders (APA, 2000; 2013) which was confirmed by the research team using the Autism Diagnostic Observation Schedule – Second Edition (ADOS-2; Lord, Rutter, DiLavore, & Risi, 2012) and the Autism Diagnostic Interview – Revised (ADI-R; Rutter, LeCouteur, & Lord, 2003).

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, coordination difficulties due to a general medical condition (e.g., cerebral palsy, hemiplegia, or 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 resulting prevalence of stimulant use in autism (DeFlippis & Wagner 2016), we elected not to exclude participants reporting stimulant use. 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, Table 1) Participants in the neurotypical group had no prior history of developmental conditions and scores on the Social Communication Questionnaire (SCQ; Rutter, Bailey, & Lord, 2003) < 8. The study was approved by the University of North Texas Health Science Center Institutional Review Board.

Table 1

Demographic and Cognitive Characteristics of the Sample by Group

		Autism (*n* = 19)		Neurotypical (*n* = 16)	
Variable	*Level*	*Freq.*	*%*	*Freq.*	*%*
Gender	Male	16	84%	7	44%
	Female	3	16%	9	56%
Race	White	16	84%	12	75%
	Black or African-American	1	5%	1	6%
	Asian	1	5%	3	19%
	American Indian or Alaska Native	1	5%	0	0%
Ethnicity	Hispanic	3	16%	1	6%
	Non-Hispanic	16	84%	15	94%

	Autism (*n* = 19)		Neurotypical (*n* = 16)		
Variable	*Mean (SD)*	*Range*	*Mean (SD)*	*Range*	*p*
Age	14.58 (9.25)	6-43	19.56 (10.53)	8-44	0.15
WASI-2 Full-Scale IQ	98.28 (16.04)	62-126	108.50 (13.46)	91-136	0.05
Non-Verbal IQ	100.00 (17.61)	68-129	105.75 (10.55)	91-125	0.26
Verbal IQ	96.78 (14.43)	61-117	109.25 (15.43)	92-142	0.02

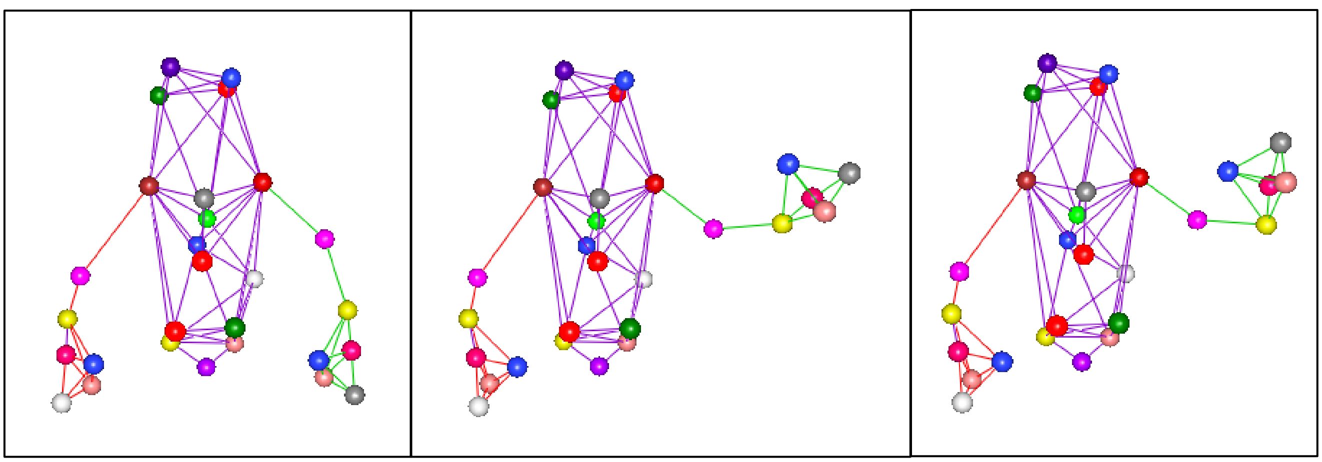
Note: IQ = Intelligence Quotient; WASI-2 = Wechsler Abbreviated Scale of Intelligence, 2nd Edition.

Apparatus

Participants interacted with customized Zeno R30 Robot (Fig. 1; Robokind, Dallas, TX, USA), a 2-foot tall humanoid robot with the appearance of a 4- to 7- year-old child. His upper body and arms have nine degrees of freedom, including three degrees of freedom in each arm devoted to the shoulder (flexion/extension, adduction/abduction, internal/external rotation) and one devoted to the elbow (flexion/extension). Zeno's movement was controlled by a NI MyRio and LabVIEW controlling joint Dynamixel RX-28 servo motors. To wave, Zeno raised his arm and then repeated elbow extension and flexion (out-in-out-in-out) with an angular displacement of 40°, before returning to the starting position for a total movement time of 7.5 seconds.

Figure 1. Participant interacting with Zeno the robot, instrumented with markers on the head, arms, and torso.

We used a 16-camera motion-capture system (Motion Analysis Corp., Santa Rosa, CA, USA) to capture the participant's three-dimensional (3D) body position at 120 Hz from 49 spherical reflective markers placed on standard anatomical landmarks (Bugnariu & Fung, 2010) and 28 markers placed on analogous locations on the robot's head, arms, and torso (see Appendix A for a list of all marker placements for the participant and the robot). The robot's legs were not instrumented, since its lower body did not move during the tasks. The markers enabled precise calculation of kinematics and joint range of motion, presenting the opportunity to quantify the accuracy and quality of participants' imitative movements. In order to calculate joint angles for the analyses presented here, we specifically considered the 3D positions of markers placed at the location (for the participant) or analogous location (for the robot) of the 7th cervical vertebra, 8th thoracic vertebra, sternum, xyphoid process, left and right medial and lateral epicondyles, and markers placed on the left and right acromion, upper arm, forearm, styloid process of the radius, and ulnar head. These markers enabled precise calculation of kinematics and joint range of motion, presenting the opportunity to quantify the accuracy and quality of participants' imitative movements.



(a) (b) (c)

Figure 2. Visual representation of motion-capture data obtained from Zeno at rest (a) and during the waving gesture at full elbow extension (b) and full elbow flexion (c) with an angular displacement of 40º.

Procedures

We obtained written parental consent for all participants and children above 7 years old were asked to sign a written assent form. We also collected demographic information (see Table 1). Participants wore fitted clothing and reflective markers on the arms, legs, and torso (see appendix A for marker locations). During testing, participants were asked to imitate Zeno and a member of the research team stood nearby to ensure task comprehension and compliance. Participants imitated six gestures: “Bump”, “Give”, “Wave”, “Celebrate”, “Hug”, “What” (for detailed descriptions see appendices B and C). We collected and analyzed six trials per arm for each gesture type.

Dynamic Time Warping

We used data from the motion-capture system to calculate the 3-dimensional position of the arm at each sample during imitation of a wave. Joint angles were calculated using these data and were used to assess imitation accuracy. The four angles of interest were: shoulder flexion/extension, shoulder adduction/abduction, internal/external shoulder rotation, elbow flexion/extension. The trigonometric equations used to calculate each joint angle based on the 3-dimensional Cartesian joint positions recorded by the motion capture system are described in greater detail in a previous publication (Simon, 2004).

We used the dynamic time warping algorithm to compare the participant’s and Zeno’s joint angles across the movement cycle, quantifying the degree of matching between them as a distance-like similarity measure. The outcome measure from dynamic time warping procedure is a *cost* value, which represents the degree of dissimilarity between the two movements independent of non-linear variations in the dimension of time, such that lower cost represents more accurate imitation. We *z*-normalized each angle trajectory by subtracting the mean from each signal and dividing by their respective standard deviations, in order to compensate for range of motion and kinematic differences between the participant and Zeno (Simon, 2004).

We added the cost values across the movement cycle for each joint angle to quantify the total discrepancy between Zeno’s wave and the participant’s imitation. Since the shoulder adduction/abduction and elbow flexion/extension angles contribute more to the waving motion than the shoulder flexion/extension and internal/external shoulder rotation angles once the arm is raised, a weighted average of the two most influential angles was also calculated as a secondary means of evaluating imitative accuracy. Weights were calculated based on Zeno's range of motion prior to normalizing joint angle trajectories. The range of motion weight was calculated as:

$$W = max(X) - min(X)$$

where *X* represents a column vector of unnormalized joint angles. The weighted average of the shoulder adduction/abduction and elbow flexion/extension angles was calculated as:

$$A_W = (W_S D_S + W_e D_e) / (W_S + W_e),$$

where W_s is the weight (based on Zeno's range of motion) of the shoulder adduction/abduction angle and D_s is the calculated dynamic time warping value for the shoulder adduction/abduction angle. The sum of the weighted average of each of the two angle trajectories was multiplied by its corresponding dynamic time warping value for the shoulder flexion/extension and internal/external shoulder rotation angles. Dynamic time warping and weighting procedures are described in greater detail elsewhere (Bugnariu et al., 2013; Ranatunga et al., 2013; Ranatunga et al., 2012; Wijayasinghe et al., 2016).

Linear Mixed Effects Modelling

Linear mixed effects modeling was used to regress log-transformed DTW onto fixed factors of group (autism, neurotypical), body movement (Bump, Give, Wave, Celebrate, Hug, What), joint movement (Shoulder flexion/extension, Shoulder abduction/adduction, Shoulder rotation, Elbow flexion/extension), and age (continuous) with a random intercept by participant (R Version 4.1.1; Bates, Machler, Bolker, & Walker, 2015). We log-transformed DTW prior to analysis to improve normality and homoskedasticity. We conducted *F*-tests for fixed effects of linear mixed effects models using Satterthwaite's method (Kuznetsova, Brockhoff, & Christensen, 2017). Estimated marginal means, standard errors, β-weights are reported in log-scale. Data points that were three or more standard deviations from the mean were determined to be outliers and removed from the analysis (0.74% of the data).

Results

A linear mixed-effects model was used to regress log-transformed DTW onto group, body movement, joint movement, arm, controlling for age and a random intercept by participant. There were significant main effects of body movement ($F_{5,1578.2}$=103.67, p<.001), joint movement ($F_{3,1573.3}$=220.64, p<.001), and arm ($F_{1,1574.0}$=14.34, p<.001). There were significant two-way interactions of Group X Joint Movement ($F_{3,1573.3}$=3.98, p=.008), Group X Body Movement ($F_{5,1578.2}$=2.28, p=.044), Joint Movement X Body Movement ($F_{15,1573.4}$=175.77, p<.001), Joint X Arm ($F_{3,1573.2}$=7.92, p<.001), Body Movement X Arm ($F_{5,1573.9}$=39.40, p<.001). There were significant three-way interactions of Group X Joint Movement X Body Movement ($F_{15,1573.4}$=3.28, p<.001), Group X Body Movement X Arm ($F_{5,1573.9}$=2.89, p=.013), and Joint Movement X Body Movement X Arm ($F_{15,1573.2}$=23.72, p<.001).

A priori comparisons of estimated marginal means of log-transformed DTW between autistic and neurotypical participants for each joint during each body movement were conducted revealed differences varying by body movement and joint movement between groups. For the bump movement, autistic participants ($M_{\text{Shoulder flexion/extension}}$ = 5.78, $SE_{\text{Shoulder flexion/extension}}$ = 0.08; $M_{\text{Elbow flexion/extension}}$ = 6.37, $SE_{\text{Elbow flexion/extension}}$ = 0.08) were worse at shoulder flexion/extension (t_{527}=-2.71, p = .007) and elbow flexion/extension (t_{519}=-3.41, p < .001) compared to neurotypical ($M_{\text{Shoulder flexion/extension}}$ = 5.47, $SE_{\text{Shoulder flexion/extension}}$ = 0.08; $M_{\text{Elbow flexion/extension}}$ = 5.98, $SE_{\text{Elbow flexion/extension}}$ = 0.08). For the give movement, autistic participants ($M_{\text{Shoulder flexion/extension}}$ = 5.70, $SE_{\text{Shoulder flexion/extension}}$ = 0.08) were worse at the shoulder flexion/extension (t_{542} = -2.84, p = .005) compared to neurotypical ($M_{\text{Shoulder flexion/extension}}$ = 5.37, $SE_{\text{Shoulder flexion/extension}}$ = 0.09). For the wave movement, autistic participants ($M_{\text{Elbow flexion/extension}}$ = 6.63, $SE_{\text{Elbow flexion/extension}}$ = 0.08) were worse at elbow flexion/extension (t_{525} = -2.12, p = .034) compared to neurotypical ($M_{\text{Elbow flexion/extension}}$ = 6.39, $SE_{\text{Elbow flexion/extension}}$ = 0.08). For the what movement, autistic participants ($M_{\text{Shoulder abduction/adduction}}$ = 6.57, $SE_{\text{Shoulder abduction/adduction}}$ = 0.08; $M_{\text{Shoulder rotation}}$ = 6.01, $SE_{\text{Shoulder rotation}}$ = 0.08) were worse at the shoulder abduction/adduction (t_{542} = -2.65, p = .008) but better at the shoulder rotation (t_{542} = 2.39, p = .017) compared to neurotypical ($M_{\text{Shoulder abduction/adduction}}$ = 6.25, $SE_{\text{Shoulder abduction/adduction}}$ = 0.09; $M_{\text{Shoulder rotation}}$ = 6.28, $SE_{\text{Shoulder rotation}}$ = 0.09). For the celebrate movement, autistic participants ($M_{\text{Shoulder flexion/extension}}$ = 6.98, $SE_{\text{Shoulder flexion/extension}}$ = 0.08) were worse at shoulder flexion/extension (t_{517} = -1.97, p = .050) compared to neurotypical ($M_{\text{Shoulder flexion/extension}}$ = 6.76, $SE_{\text{Shoulder flexion/extension}}$ = 0.08). Autistic and neurotypical participants did not differ on any joint movements for the hug movement.

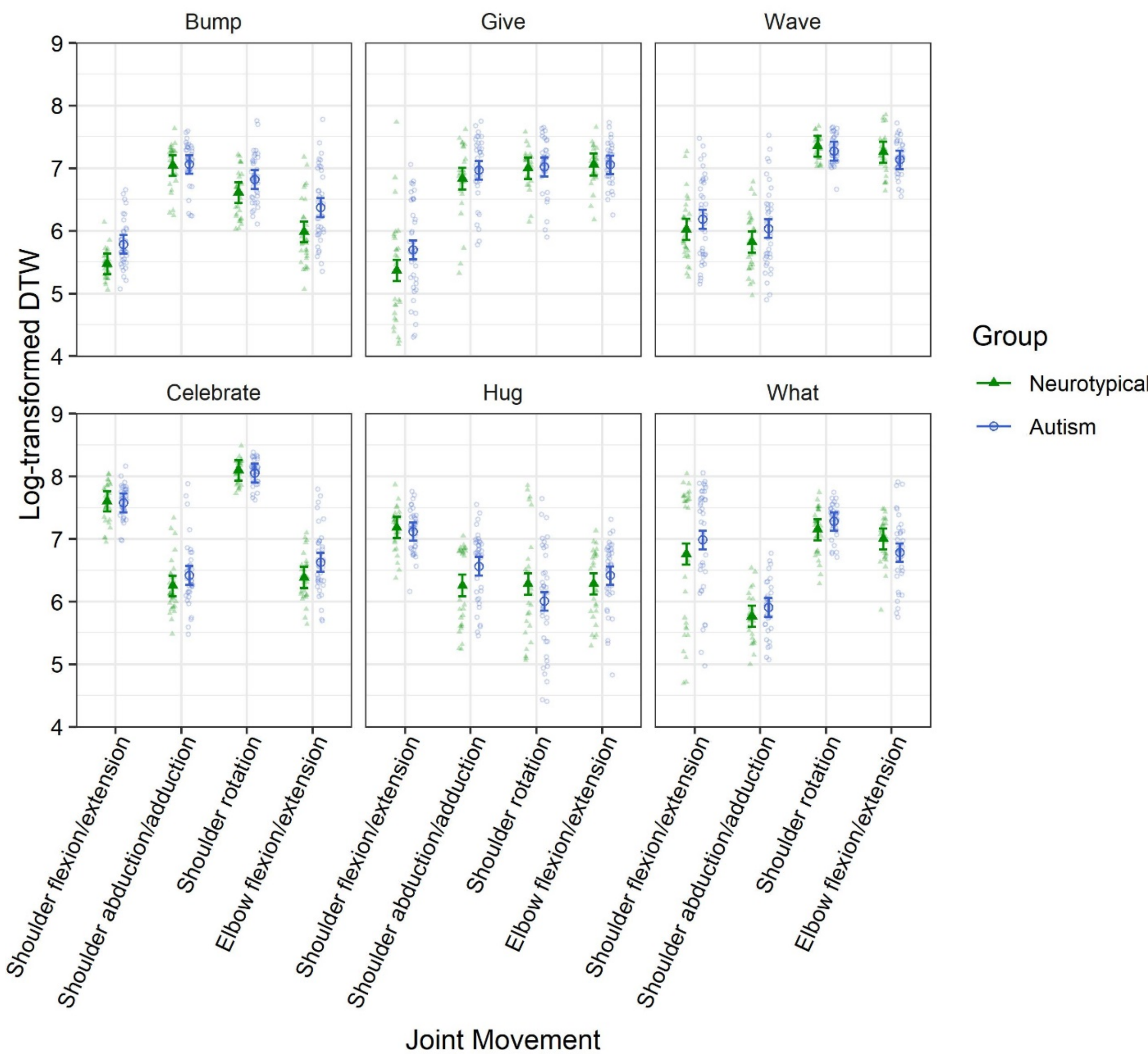


Figure 3. Autistic participants had worse scores on bump at shoulder flexion/extension and elbow flexion/extension, give at shoulder flexion/extension, wave at elbow flexion/extension, what at shoulder abduction/adduction, and celebrate at shoulder flexion/extension compared to neurotypical participants. Autistic participants had better scores for what at shoulder rotation. Solid points indicate estimated marginal means, bars indicate 95% confidence intervals, and transparent points indicate raw data.

Discussion

The objective of this pilot study was to ascertain whether autistic and neurotypical children could be differentiated based on quantitative differences in the kinematics of their imitative gesturing. To reduce variability in the to-be-imitated gesture, we used a robot interaction partner rather than a human actor. Children's ability to learn from and engage in social behaviors with robot partners is also of interest as a potential method of intervention delivery, but the relative dearth of available data on the effectiveness of this method in autism warranted investigation (Diehl, Schmitt, Villano, & Crowell., 2012). The present pilot study provides early data suggesting that autistic children do effectively engage with robots in imitative gesturing on a qualitative level but have notable quantitative differences in the kinematics of their movements.

Examining individual joint movements within arm movements revealed significant differences between the autistic and neurotypical participants. Autistic participants differed on flexion and extension movements of the shoulder and elbow across multiple body movements. Autistic individuals had larger DTW scores (i.e., poorer performance in imitating the movements of the robot) when flexing or extending the shoulder or elbow compared to neurotypical individuals on the four of the six movements; bump, give, wave, and celebrate body movements. Notably, the flexion or extension of the shoulder and elbow is critical to the imitation of these movements with the largest change in joint angle being occurring at this plane-joint combination. This may indicate that while neurotypical participants were attempting to match the largest change in joint angle, and likely the most perceptually noticeable, when imitating the robot's movements, the autistic participants failed to do so. This difference in imitation at the critical joints of a movement may be the underlying reason that imitation in autism is perceived as qualitatively different from their neurotypical peers.

The largest group differences were found in during the bump and give body movements and were notably similar to one another and different from the other movements. These two movements required forward, unilateral extension of the arm away from the body, whereas others required upward and/or bilateral motion. Notably, of the six movements in our testing scenario, the bump and give movements most closely approximated social engagement, since the participant was reaching toward the robot and often came close to touching his hand.

Given the complexity of these results, planned future analyses will include models accounting for the potential covariance of imitative accuracy with age, symptom severity, and scores on developmental motor assessments. Finally, analysis of the eye-tracking data collected during this study may yield important information about the potential source of imitative inaccuracy in autism. For participants who engage in atypical visual tracking strategies, inaccurate information about motion characteristics of the robot may relate to the degree of inaccuracy observed in their attempts to imitate Zeno's movement.

Conclusion

Our results suggest that differences in imitative gesturing in autism may stem from fundamental differences in the kinematics of their movements, rather than purely from a higher-order difference in social communication ability. This finding is in alignment with prior work suggesting that overreliance on proprioceptive feedback and dysfunction in internal models of action may increase difficulty with complex, goal-directed motor skills like imitation (Izawa et al., 2012; Haswell et al., 2009; MacNeil & Mostofsky, 2012; Mostofsky & Ewen, 2011; Pillai et al., 2018). Although our sample was small, important distinctions between autism and neurotypical groups were observed in the coordination of the arm during imitation of a robot, as hypothesized. The variability observed among autistic participants in our study reflects that reported in many other studies of autism, and may be indicative of phenotypes within this clinical population that are separable based on their motor skills.

Contributions

Contributed to conception and design: HLM, IW, DOP, GMS, DB, RMP, NLB, LSH

Contributed to acquisition of data: HLM, IW, DOP, GMS, DB, RMP, NLB

Contributed to analysis and interpretation of data: NEF, HLM, IW, DOP, LSH

Drafted and/or revised the article: NEF, HLM

Approved the submitted version for publication: NEF, HLM, IW, DOP, GMS, DB, RMP, NLB, LSH

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Data and Supplementary Material Accessibility

The data and code 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 data and code, it cannot be shared at this time.

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APPENDIX

A.

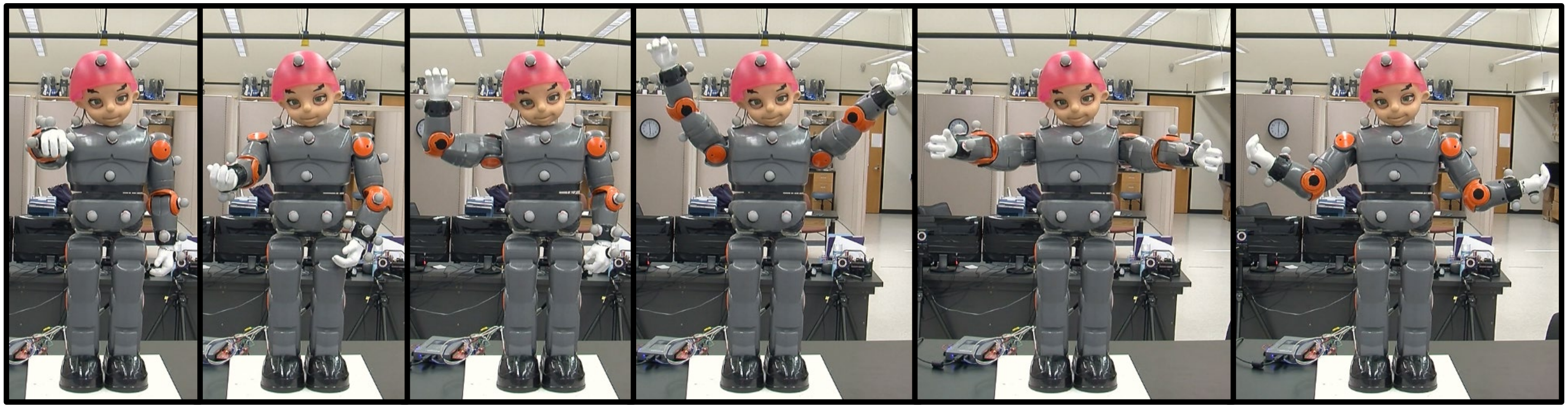
Child Marker Placements	Zeno Marker Placements
Right front of head (on hat)	Right front of head (on hat)
Right back of head (on hat)	Right back of head (on hat)
Left front of head (on hat)	Left front of head (on hat)
Left back of head (on hat)	Left back of head (on hat)
7th cervical vertebra	7th cervical vertebra
8th thoracic vertebra	8th thoracic vertebra
Sternum	Sternum
Xiphoid process	Xiphoid process
Left acromion	Left acromion
Left upper arm	Left upper arm
Left lateral epicondyle	Left lateral epicondyle
Left medial epicondyle	Left medial epicondyle
Left forearm	Left forearm
Left radius styloid process	Left radius styloid process
Left ulnar head	Left ulnar head
Right scapula	Right scapula
Right acromion	Right acromion

Right upper arm	Right upper arm
Right lateral epicondyle	Right lateral epicondyle
Right medial epicondyle	Right medial epicondyle
Right forearm	Right forearm
Right radius styloid process	Right radius styloid process
Right ulnar head	Right ulnar head
Left anterior superior iliac spine	Left anterior superior iliac spine
Left posterior superior iliac spine	Left posterior superior iliac spine
Right anterior superior iliac spine	Right anterior superior iliac spine
Right posterior superior iliac spine	Right posterior superior iliac spine
Sacrum	Sacrum
Right hamstring	
Right thigh	
Right lateral knee	
Right medial knee	
Right shank	
Right medial ankle	
Right lateral ankle	
Right heel	
Right toe	
Right 2nd metatarsal	
Right 5th metatarsal	
Left thigh	
Left lateral knee	
Left medial knee	
Left shank	
Left lateral ankle	
Left medial ankle	
Left heel	
Left toe	
Left 2nd metatarsal	
Left 5th metatarsal	

B.

Gesture	Description
Bump	One arm extending forward, fist closed, palm facing down
Give	One arm extending forward, open hand, palm facing up
Wave	One arm extending up and to the side, moving back and forth, open hand, palm facing forward
Celebrate	Both arms extending up and out, open hands, palms facing forward
Hug	Both arms extending out and forward, palms facing in
What	Both arms extending out and upward, open hands, palms facing up

C.



Zeno performing each gesture from left to right: Bump, Give, Wave, Celebrate, Hug, What. The first 3 movements are unimanual and the last 3 movements are bimanual.