Clinical Biomechanics 106 (2023) 105987

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

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

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ARTICLE INFO

Keywords:
Autism
Imitation
Gesture
Dynamic time warping
Robot

ABSTRACT

Background: 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 socially stressful interaction partners (e.g., robots). In this study, we aimed to quantify differences in imitative gesturing between autistic and neurotypical development during human-robot interaction.

Methods: 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 and work contribution to determine how each joint angle was producing the movements.

Findings: Results revealed differences between autistic and neurotypical participants in imitative accuracy and work contribution, primarily in the movements requiring unilateral extension of the arm. Autistic individuals imitated the robot less accurately and used less work at the shoulder compared to neurotypical individuals.

Interpretation: These findings indicate differences in autistic participants' ability to imitate an interactive robot. These findings build on our understanding of the underlying motor control and sensorimotor integration mechanisms that support imitative gesturing in autism which may aid in identifying appropriate intervention targets.

1. Introduction

Prior to the development of language, imitation and nonverbal communicative gesturing play a crucial role in early learning development (Meltzoff and 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 et al., 1979) and social interaction (Iacoboni, 2005).

Substantial evidence indicates that autistic individuals have specific difficulties with imitating an observed motor action (for reviews, see Smith and Bryson, 1994; Rogers, 1999; Williams et al., 2004) as well as difficulty inferring intent from gestures (Bhat et al., 2011). These differences may stem from atypical functioning of the mirror neuron system (MNS) (Martineau et al., 2010; Williams et al., 2001), and/or from differences in general motor planning skills (Gonzalez et al., 2013; Green et al., 2009; Hughes, 1996; Miller et al., 2021; Scharoun and Bryden, 2016). Specifically, differences in imitative gesturing are often

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https://doi.org/10.1016/j.clinbiomech.2023.105987
Received 13 September 2022; Accepted 10 May 2023
Available online 13 May 2023

observed (de Marchena et al., 2018; Ellawadi and Weismer, 2014; McAuliffe et al., 2017; Mostofsky et al., 2006; Rogers et al., 1996; Smith and Bryson, 2007; Young et al., 2011), and distinguishes autism from other developmental, movement, and attention disorders (Dewey et al., 2007; MacNeil and Mostofsky, 2012; Minshew et al., 2004; Rogers et al., 2003; Veness et al., 2012). Further, prior studies have demonstrated the ability of autistic individuals to reproduce goal-directed motor actions with respect to using pointing and intransitive gestures (Gowen et al., 2020; Hamilton et al., 2007; Vabalas et al., 2020) or transitive gestures (i.e. gesturing with objects; Cossu et al., 2012; Hamilton et al., 2007; Hobson and Lee, 1999; Hobson and Hobson, 2008; Stone et al., 1997) to achieve a modeled end state, especially for meaningful actions (Carmo et al., 2013). However, the nature of action used to reach that end state varies, suggesting that *emulation* in autism may be preserved despite differences in *imitative* accuracy, especially in continuous gestures without a clearly-defined and modeled end state. The goal of this study was to examine autistic individuals' imitative accuracy of continuous, meaningful, conventional gestures.

Compared to behavioral coding of imitative gesturing, fewer studies have characterized imitation differences in autism using precisely quantifiable methods (e.g., Anzulewicz et al., 2016; Gowen et al., 2020; Tunçgenç et al., 2021). Current practice for assessing the quality of imitation and gesturing relies heavily on caregiver reports (e.g., Autism Diagnostic Interview–Revised) and behavioral observation or video coding (e.g., Watson et al., 2013). Fundamental motor coordination problems may underlie difficulties with imitative accuracy for higher-order, more complex motor behaviors such as gesturing.

1.1. 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 et al., 2007). At present, most intervention approaches involve direct interaction between an 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., Hopkins et al., 2011; Kandalaft et al., 2013) and robots (Boucenna et al., 2016; So et al., 2017; Srinivasan et al., 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 and Cangelosi, 2014; Cangelosi and Schlesinger, 2015). These advancements opened the possibility of human-robot interactions in which robots "teach" movements to be imitated by humans. Previous studies have specifically highlighted 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 et al., 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.

1.2. Assessing accuracy of imitated movement

Studies have attempted to quantify the accuracy of imitated movements by autistic individuals (Rogers et al., 2003; Salowitz et al., 2013; Toth et al., 2006; Tunçgenç et al., 2021; Wild et al., 2012). For example, Salowitz et al. (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; Romero et al., 2018; Salowitz et al., 2013; Toth et al., 2006). 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. Additionally, the observational coding of behavior is limited in the ability to delineate the exact aspects of a movement that may lead to atypical appearance of a gesture or inaccurate gesture praxis.

In contrast, researchers have begun using more precise measures of kinematics of imitation in other populations (Hermsdörfer et al., 1996; Reader et al., 2018; Wong et al., 2019) and in autism (Gowen et al., 2020; Hayes et al., 2016; Tunçgenç et al., 2021; Vabalas et al., 2020; Wild et al., 2012) using direct measurement of biomechanical or kinematic data to quantify the degree to which an imitative gesture matches positional elements of a target movement in autism. Both temporal and positional elements of a gesture are used to convey functional meaning. However, 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. Additionally, autistic participants may have slower action imitation which could result from a number of different factors including atypical myelination and connectivity in primary motor cortex leading to delayed motor signaling that are not necessarily attributed to difficulties in imitative accuracy (Carper et al., 2015). The current study used a dynamic time warping approach to examine the positional accuracy of imitative gesturing in autistic individuals.

Dynamic Time Warping (DTW; Berndt and 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. DTW allows an elastic shifting of the time axes of time series data streams to accommodate the comparison of data streams that have similar overall shapes, but out of phase (Keogh and Ratanamahatana, 2005). This is done through a recursive process that dynamically aligns the data streams by minimizing the distance between the data streams while maintaining the boundary conditions, continuity, and monotonicity (Keogh and Ratanamahatana, 2005). DTW is best used when comparing the similarity between data streams that follow similar shapes across a movement cycle, but which may be conducted at a different speed or with time-delays (Ranatunga et al., 2013). Upper extremity movement is temporally variable and complex (Rab et al., 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 time series 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. This allowed us to present Zeno's gestures slowly, so that the participant had ample time to observe components of the movement, without penalizing participants for whether they could precisely match his speed.

1.3. Objectives and hypotheses

We aimed to quantify imitative accuracy in autistic individuals compared to neurotypical 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 autistic and neurotypical participants and a humanoid robot (Bugnariu et al., 2013; Ranatunga et al., 2012; Ranatunga et al., 2013; 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 and 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. Additionally, we were able to measure multiple specific joint angles that contribute to the imitation of each gesture. This allows us to determine what the exact aspects of the movements may be contributing to the observed differences in imitation accuracy. We hypothesized that autistic participants would produce less accurate imitations of a robot's waving movement, reflected in higher DTW values, than their neurotypical counterparts. This work builds on previous literature by examining gestural imitation differences between autistic and neurotypical participants using analytical approaches that allow comparisons independent of temporal constraints.

Following preliminary analyses of the imitative accuracy of autistic participants, we also investigated the work performed at each of the joint angles during each of the movements. We aimed to determine if the amount of work done at the individual joint angles may be different, indicating that autistic participants are using their arms in a different way, and potentially lead to differences in imitative accuracy. The preliminary analyses indicated that there were significant differences in shoulder flexion/extension for movements involving anterior arm movements and shoulder abduction/adduction movements involving lateral arm movements. We hypothesized that autistic participants may have worse imitation accuracy at these joint angles for these movements because they use more work at the elbows and less work at the shoulders to limit the potential disruption of their postural stability.

2. Method

2.1. 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 autistic 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 et al., 2012) and the Autism Diagnostic Interview – Revised (ADI-R; Rutter et al., 2003b).

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 (DeFilippis and 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 et al., 2003a) < 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.

		Autistic (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%

	Autistic (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.

2.2. Apparatus

Participants interacted with customized Zeno R30 Robot (Fig. 1; Robokind, Dallas, TX, USA), a 2-ft-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. For example, 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 s. Zeno's movements were programmed based on position data captured by a Microsoft Kinect from movements performed by a member of the research team.

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 and Fung, 2010) and 28 markers placed on analogous locations on the robot's head, arms, and torso (Fig. 2; see Appendix A for a list of all marker placements for the participant and the robot). Neither the participants' nor the robot's hands or fingers were instrumented to reduce sensory related discomfort of the markers and because these segments were not core components of any of the movements. The robot's legs were not instrumented, since its lower body did not move during the tasks. The markers enabled precise

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

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.

We used two force-plates embedded in a platform to measure ground reaction force at 120 Hz. Similar force plates have been used previously to determine differences in movements in autistic and neurotypical individuals (Fears et al., 2023; Miller et al., 2019). This data was integrated with the kinematic data in Visual3D (C-Motion, Inc., Germantown, MD, USA) to calculate powers for each of the joint angles at the shoulder and elbow (see *Work Calculation* section for more detail).

2.3. Procedures

We obtained written consent or parental consent for all participants and children 7 through 17 years of age 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. A member of the research team stood nearby to ensure task comprehension and compliance. The instructions were: "In just a moment, Zeno is going to start to move. I want you to do exactly what he does like you are looking in a mirror. If he moves this side (proctor points to Zeno's left side) you move this side (proctor points to participant's right side)." Participants imitated six gestures: "Bump", "Give", "Wave", "Celebrate", "Hug", "What" (for detailed descriptions see Appendices B and C). For unimanual movements (i.e., "Bump", "Give", "Wave"), participants performed five continuous repetitions using one arm followed by five continuous repetitions using the second arm for each gesture. For bimanual movements, (i.e., "Celebrate", "Hug", "What"), participants performed five continuous repetitions using both arms simultaneously for each gesture. A video demonstration of Zeno's movements is provided in *Supplementary Material.*

2.4. Dynamic time warping calculation

We used data from the motion-capture system to calculate the 3-dimensional position of the arm at each sample during the imitation of each gesture. 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

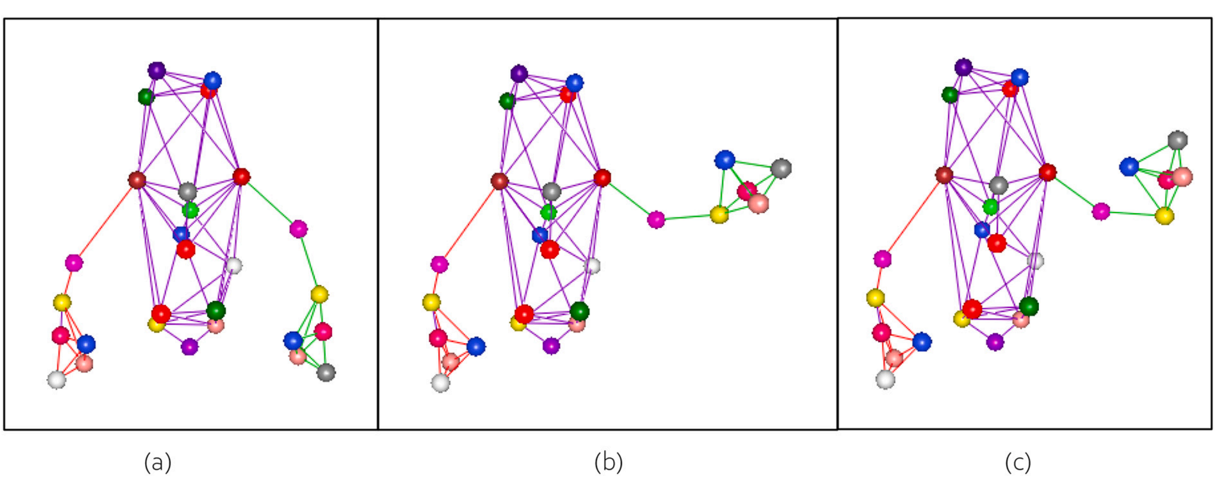


Fig. 2. Visual representation of motion-capture data obtained from Zeno at rest (a) and during the waving gesture at full elbow extension (b) and full elbow flexion (c) with an angular displacement of 40°.

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 gesture and the participant's imitation. Dynamic time warping is described in greater detail elsewhere (Bugnariu et al., 2013; Ranatunga et al., 2012; Ranatunga et al., 2013; Wijayasinghe et al., 2016).

2.5. Work calculation

We used the data from the motion capture system to calculate the 3-dimensional position of each arm and the ground reaction force from the force plates to calculate the power of each joint movement per frame in Visual3D (C-Motion, 2022). Work is the mechanical energy flow over time (Winter, 2009). Work is used here to determine differences in the contribution of each joint angle to each of the movements. Positive power values for each frame were used to calculate work generation for each individual joint movement via a custom MATLAB (The MathWorks, 2022) script. Work for the length of each trial was calculated as:

$$Work_{joint\ movement} = \int_{Time_1}^{Time_n} Power_{joint\ movement} dTime$$

Where $Power_{joint\ movement}$ is the power of an individual joint movement (e.g., shoulder flexion/extension) at a single time point, $Time_1$ is the first frame of the trial, $Time_n$ is the last frame of the trial, dTime is the change in time, and $Work_{joint\ movement}$ is the total work generated by the individual joint movement across an entire trial.

2.6. Linear mixed effects modeling

Linear mixed effects modeling (lme4: lmer, Bates et al., 2015) was used to regress log-transformed DTW onto fixed factors of group (autistic, neurotypical), body movement (Bump, Give, Wave, Celebrate, Hug, What), joint movement (Shoulder flexion/extension, Shoulder abduction/adduction, Shoulder rotation, Elbow flexion/extension), arm (Left, Right), and age (continuous) with a random intercept by participant (R Version 4.1.1). Linear mixed effects modeling was also used to regress log-transformed work for the shoulder angles and the elbow angles onto group, body movement, arm, and age with a random intercept by participant. Only joint movements during the corresponding trial were used for unimanual movements (e.g., left arm joint movements were analyzed during left arm wave). Joint movements for both arms were used for bimanual movements. We log-transformed DTW and work 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 et al., 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 of all scores from all participants were determined to be outliers and removed from the analysis (0.74% of the data).

3. Results

3.1. Dynamic time warping analysis

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 ($F_{3,1573.3} = 220.64$, $p < .001$), arm ($F_{1,1574.0} = 14.34$, $p < .001$), and age ($F_{1,35.0} = 7.29$, $p = .011$). 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 ($F_{15,1573.2} = 23.72$, $p < .001$) (Fig. 3).

A priori comparisons of estimated marginal means of log-transformed DTW between autistic and neurotypical participants for each joint movement during each body movement were conducted revealed differences varying by body movement and joint movement between groups (Table 2). For the bump movement, autistic participants 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. For the give movement, autistic participants were worse at the shoulder flexion/extension ($t_{542} = -2.84$, $p = .005$) compared to neurotypical. For the wave movement, autistic participants were worse at elbow flexion/extension ($t_{525} = -2.12$, $p = .034$) compared to neurotypical. For the what movement, autistic participants 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. For the celebrate movement, autistic participants were worse at shoulder flexion/extension ($t_{517} = -1.97$, $p = .050$) compared to neurotypical. Autistic and neurotypical participants did not differ on any joint movements for the hug movement.

3.2. Work analyses

A linear mixed-effects model was used to regress log-transformed work onto group, body movement, and joint angle controlling for arm and age and a random intercept by participant. There were significant main effects of movement ($F_{5,1579.20} = 37.17$, $p < .001$), joint angle ($F_{3,1575.91} = 439.55$, $p < .001$), and arm ($F_{1,1575.92} = 167.45$, $p < .001$). These were qualified by a Movement X Joint Angle interaction ($F_{15,1575.36} = 25.63$, $p < .001$, Fig. 4) and a Group X Joint Angle interaction ($F_{3,1575.90} = 3.50$, $p = .015$, Fig. 4).

A priori comparisons of estimated marginal means of log-transformed work between autistic and neurotypical participants during each body movement and joint angle were conducted revealed a difference between groups for the Wave shoulder flexion/extension ($t_{172} = 2.67$, $p = .009$, Fig. 4). Autistic participants (M = -1.64, SE = 0.13) used less shoulder flexion/extension work during the Wave movement compared to neurotypical participants (M = -1.23, SE = 0.14). There were group differences trending toward significance for Wave shoulder abduction/adduction ($t_{175} = 1.75$, $p = .082$, Fig. 4) and What shoulder flexion/extension ($t_{182} = 1.779$, $p = .077$, Fig. 4). Autistic participants (M = -1.88, SE = 0.13) used less shoulder abduction/adduction work during the Wave movement compared to neurotypical participants (M = -1.61, SE = 0.14). Autistic participants (M = -1.84, SE = 0.13) used less shoulder flexion/extension work during the What movement compared to neurotypical participants (M = -1.55, SE = 0.14).

4. Discussion

The objective of this pilot study was to ascertain whether autistic and neurotypical individuals 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. Participant'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 et al., 2012).

The key results from this study indicate that autistic participants do effectively engage with robots in imitative gesturing on a qualitative

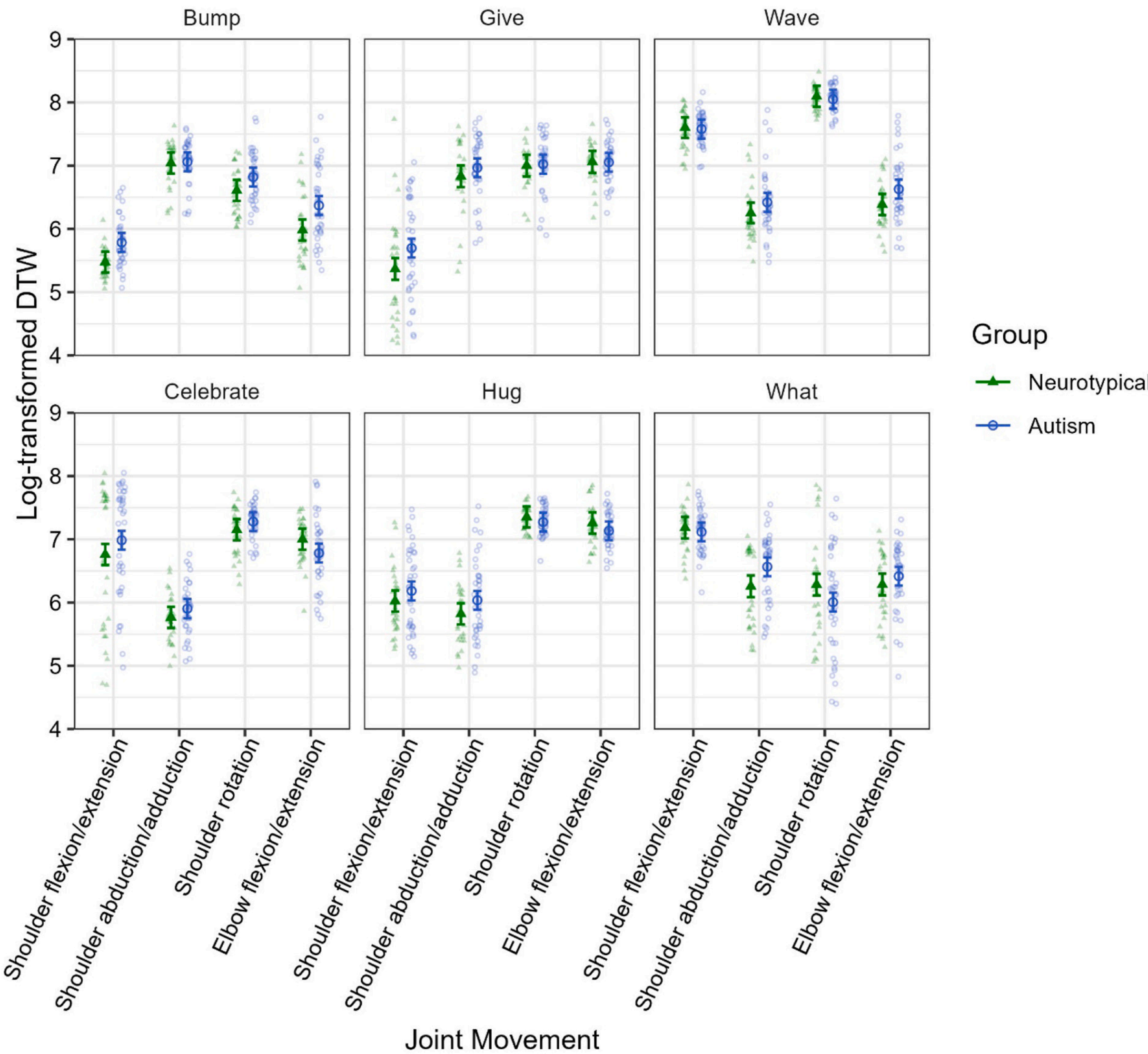


Fig. 3. Autistic participants had worse scores on bump at shoulder flexion/extension and elbow flexion/extension, give at shoulder flexion/extension, wave at elbow flexion/extension, what at shoulder abduction/adduction, and celebrate at shoulder flexion/extension compared to neurotypical participants. 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.

level but have notable quantitative differences in the kinematics of their movements. Additionally, this study confirms that DTW can be used to delineate the individual joint movements that underlie the observed differences in imitative accuracy in autism.

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.

The secondary analysis of the work performed at the individual joint angles was primarily inconclusive, with few differences between autistic and neurotypical individuals. The only significant difference between groups was of the work done at shoulder flexion/extension during the wave movement. Although this finding supports the hypothesis that autistic individuals may limit the work they perform at the shoulder joint, the evidence is weak.

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

Table 2
A priori comparisons for each joint movement of each body movement between autistic and neurotypical participants.

Body Movement		Autism		Neurotypical		
		M	*SE*	*M*	*SE*	*p*
Bump	Shoulder flexion/ extension	5.78	0.08	5.47	0.08	0.007
	Shoulder Abduction/ adduction	7.06	0.08	7.04	0.08	0.871
	Shoulder rotation	6.82	0.08	6.61	0.08	0.066
	Elbow flexion/ extension	6.37	0.08	5.98	0.08	0.001
Give	Shoulder flexion/ extension	5.70	0.08	5.37	0.09	0.005
	Shoulder Abduction/ adduction	6.97	0.08	6.83	0.09	0.250
	Shoulder rotation	7.02	0.08	7.00	0.09	0.839
	Elbow flexion/ extension	7.05	0.08	7.06	0.09	0.950
Wave	Shoulder flexion/ extension	7.58	0.08	7.60	0.08	0.852
	Shoulder Abduction/ adduction	6.42	0.08	6.25	0.08	0.137
	Shoulder rotation	8.05	0.08	8.10	0.08	0.685
	Elbow flexion/ extension	6.63	0.08	6.39	0.08	0.034
Celebrate	Shoulder flexion/ extension	6.98	0.08	6.76	0.08	0.050
	Shoulder Abduction/ adduction	5.90	0.08	5.77	0.08	0.229
	Shoulder rotation	7.28	0.08	7.15	0.09	0.269
	Elbow flexion/ extension	6.78	0.08	7.00	0.08	0.055
Hug	Shoulder flexion/ extension	6.18	0.08	6.02	0.08	0.161
	Shoulder Abduction/ adduction	6.04	0.08	5.82	0.08	0.060
	Shoulder rotation	7.27	0.08	7.35	0.08	0.482
	Elbow flexion/ extension	7.13	0.08	7.26	0.09	0.284
What	Shoulder flexion/ extension	7.12	0.08	7.18	0.09	0.565
	Shoulder Abduction/ adduction	6.57	0.08	6.26	0.09	0.008
	Shoulder rotation	6.01	0.08	6.28	0.09	0.017
	Elbow flexion/ extension	6.42	0.08	6.29	0.09	0.259

this study may yield important information about the potential source of imitative inaccuracy in autism. Specifically, recent work has shown that autistic individuals may spend less time looking at relevant body parts when observing movement demonstrations for imitation (Gowen et al., 2020). 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.

4.1. Limitations

This pilot study was not without limitations. The experimental setup using the full set of kinematic markers and Zeno may not be easily replicable in a clinical setting. Given the results, it is likely that fewer markers would be needed for determining DTW in a clinical setting, especially if they were carefully located to enhance detection of shoulder flexion/extension and abduction/adduction. Despite the potential for simpler options, such as video, for providing imitation instructions, the use of a humanoid robot instructor has multiple strengths. The humanoid robot instructor provides near life-size, real-time 3-dimensional information to participants that may be especially important for supporting the imitation of autistic individuals that may have difficulty intuitively mapping the movement of another person's body to their own. Second, the use of a robot to conduct the intervention has been shown to enhance engagement from autistic participants (Srinivasan et al., 2016; Zheng et al., 2016). Although we did not formally survey participants about their perceptions of Zeno, numerous participants mentioned enjoying their interactions with Zeno to the research team member proctoring the testing.

Another limitation is that Zeno's joints and movements cannot be identical to that of a human, as Zeno's joints do not move in exactly the way that human joints move, especially for the "bump" and "give" movements. However, if this was a primary driver of difficulty with imitative accuracy in our tasks, we would have expected to see similar effects in the autistic and neurotypical groups. Instead, we observed greater difficulty with imitative accuracy among autistic compared to neurotypical participants, implicating difficulties with the planning and execution of socially-engaging movements rather than technical constraints of the robot's motion.

The current study also strictly examined imitative accuracy and did not test whether autistic participants could emulate the goal of a movement despite differences in imitation. Future research should further examine differences in imitation and emulation by providing separate imitation and emulation instructions along with a clearly defined goal outcome that can be used to differentiate between these two categories.

Another potential limitation is the uneven gender distribution in our sample of autistic participants. Although this is a persistent problem in autism research and clinical care with boys being four times more likely to be diagnosed than girls (Maenner et al., 2021), future studies of imitation should exam potential differences in imitation between autistic boys and autistic girls.

Additionally, the wide age range of the current study is a potential limitation. However, we focused on meaningful, conventional, intransitive gestures that required little strategy to execute. Additionally, many of these gestures were likely familiar to the participants, even at the youngest ages, as these gestures are typically used in early childhood and have been shown to begin to be used by autistic children as young as 18–36 months of age (Delehanty and Wetherby, 2021; Özçalışkan et al., 2016).

Finally, autistic participants in our study did not consistently demonstrate clear boundaries between the end of one movement and the initiation of the next repetition, preventing us from segmenting trials within an action type to meaningfully examine within-subjects variability. Future studies should take care to include sufficiently-long intertrial intervals to enable participants to return to rest before initiation of subsequent movements. This is a particularly important consideration for populations prone to discoordination and/or protracted information processing.

5. 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 (Haswell et al., 2009; Izawa et al., 2012; MacNeil and Mostofsky, 2012; Mostofsky and Ewen, 2011; Pillai et al., 2018). Although our sample was small, important distinctions between autistic 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.

Supplementary data related to this article can be found online at

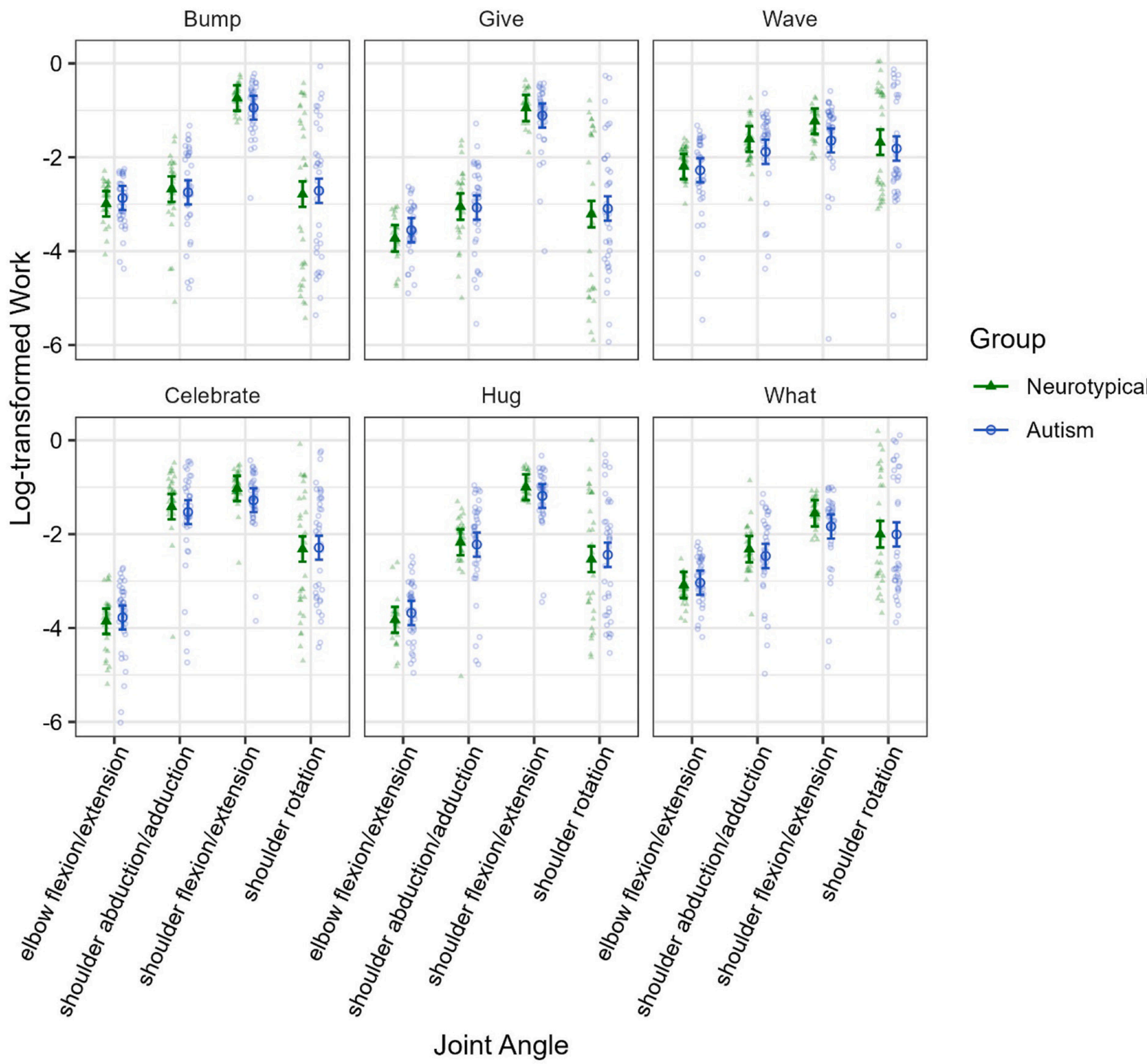


Fig. 4. Autistic participants used less work at shoulder flexion/extension for Wave compared to neurotypical participants. There were trends near significance for autistic participants using less work at shoulder abduction/adduction for Wave and less work at shoulder flexion/extension for What compared to neurotypical participants. Solid points indicate estimated marginal means, bars indicate 95% confidence intervals, and transparent points indicate raw data.

https://doi.org/10.1016/j.clinbiomech.2023.105987.

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.

Author note

Please note that throughout this manuscript, we use identity-first language, in accordance with preferences expressed by many autistic self-advocates in our studies and in the community, as well as in recent best-practice guidelines (see Bottema-Beutel et al., 2020, *Autism in Adulthood* and Botha et al., 2021, *Journal of Autism & Developmental Disorders*). In doing so, it is not our intention to diminish or invalidate the preferences or perspectives of those who prefer person-first language. We recognize that identity is deeply personal and affirm that all individual preferences regarding the language used to express one's own identity are valid and should be respected. 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.

Funding information

This work was funded in part by grants from the National Science Foundation [SMA-1514495; NRI-1208623; CPS-1035913]; the National Center for Translational Sciences [KL2-TR001103]; Texas Medical Research Consortium [RI-6027; RoDiCA]; and National Institute of Mental Health [K01-MH107774].

Declaration of Competing Interest

Haylie L Miller reports financial support was provided by National Institutes of Health. Haylie L Miller reports financial support was

provided by National Science Foundation.

Acknowledgements

We are grateful to the individuals and families who voluntarily contributed their time and effort to this research study as participants and as part of an advisory group. They are valuable members of the research team, and without them, this work would not be possible.

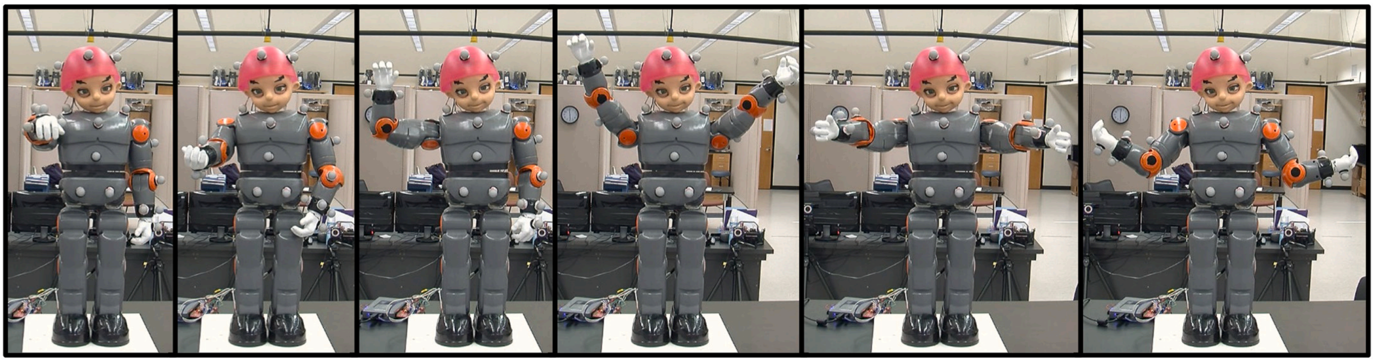
Appendix A

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	

Appendix 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

Appendix 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.

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