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Research Note

Accuracy of the NDI Wave Speech Research System

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Purpose: This work provides a quantitative assessment of the positional tracking accuracy of the NDI Wave Speech Research System.

Method: Three experiments were completed: (a) static rigid-body tracking across different locations in the electromagnetic field volume, (b) dynamic rigid-body tracking across different locations within the electromagnetic field volume, and (c) human jaw-movement tracking during speech. Rigid-body experiments were completed for 4 different instrumentation settings, permuting 2 electromagnetic field volume sizes with and without automated reference sensor processing.

Results: Within the anthropometrically pertinent "near field" (< 200 mm) of the NDI Wave field generator, at the 300-mm^3 volume setting, 88% of dynamic positional errors were < 0.5 mm and 98% were < 1.0 mm. Extreme tracking errors (> 2 mm) occurred within the near field for < 1% of position samples. For human jaw-movement tracking, 95% of position samples had < 0.5 mm errors for 9 out of 10 subjects.

Conclusions: Static tracking accuracy is modestly superior to dynamic tracking accuracy. Dynamic tracking accuracy is best for the 300-mm^3 field setting in the 200-mm near field. The use of automated head correction has no deleterious effect on tracking. Tracking errors for jaw movements during speech are typically < 0.5 mm.

Key Words: NDI wave, EMA, speech kinematics

The Wave Speech Research System (NDI; Waterloo, Ontario, Canada) is an electromagnetic articulography (EMA) system that supports three-dimensional (3D) tracking of 5 or 6 degree-of-freedom (5-DOF, 6-DOF) sensors in one of two electromagnetic field volume settings (300 mm^3 or 500 mm^3). 5-DOF sensors allow tracking of *x, y,* and *z* spatial coordinates, as well as angular coordinates characterizing rotation about the transverse axis (pitch) and anterior–posterior axis (roll). 6-DOF sensors have the added capacity for tracking angular coordinates characterizing rotation about the inferior–superior axis (yaw). The standard NDI Wave (used for the current work) has eight input channels (each 6-DOF sensor requires two channels; each 5-DOF sensor requires one channel) and records sensor movements with a 100-Hz sampling rate. A hardware upgrade is available to extend the sampling rate up to 400 Hz. Moreover, two NDI Wave system control units can be synchronized, allowing 16 total input channels.

The NDI Wave follows the basic operating principles of two-dimensional magnetometer systems (see Perkell et al., 1992). In short, a signal of varying strength is induced in a receiver (sensor) via an alternating electromagnetic field, generated by a transmitter. The strength of the induced signal varies with the distance and relative orientation between the receiver and the transmitter. Thus, sensor location can be derived from signal strength, but changes in sensor orientation confound the relationship. In the simplest case, when the long axes of the receiver and transmitter coils maintain a parallel relationship, sensor position registration is straightforward. However, changes in sensor orientation result in potential increases in tracking error. Perkell et al. (1992) refer to this as the problem of *rotational misalignment*. In practical application, rotational misalignment is particularly likely for tongue and jaw sensors as a result of variations in pitch. In principle, the hardware and software design of 3D magnetometer systems can eliminate the problem of rotational misalignment (Kaburagi, Wakamiya, & Honda, 2005). However, for the 3D NDI Aurora system, a predecessor to the NDI Wave with a 40-Hz sampling rate, both sensor orientation and distance affect tracking accuracy (Frantz, Wiles, Lies, & Kirsch, 2003).

Adapted from the Aurora system (Frantz et al., 2003; Kröger, Pouplier, & Tiede, 2008), the NDI Wave has design features, such as real-time movement data display and automated head-movement compensation,

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that may bolster the development of clinical applications (cf., Katz et al., 2007). The electromagnetic field generator for the NDI Wave system is a small, mountable box designed to be placed in profile to the human subject. The internal hardware design and tracking algorithms used in the NDI Wave are proprietary. Consequently, it is unclear how the Aurora and Wave systems are different other than in sampling rate.

The only commercially available, comparable 3D EMA system is the Carstens AG500 (Carstens Medizinelectronik, Lenglern, Germany). The AG500 differs from the basic NDI Wave system in that the field generator is larger (albeit less portable), and it has a larger number of input channels and a higher sampling rate. The AG500 field generator is composed of six transmitter coils arranged spherically in an acrylic housing that surrounds the human subject. The AG500 system can track 12 sensors with 5 DOFs at 200 Hz. A noteworthy feature of the AG500 is that the design and measurement principles that underlie the instrument are thoroughly documented and publicly available (Kaburagi et al., 2005; Zierdt, Hoole, & Tillmann, 1999).

The aim of the current work was to provide an appraisal of NDI Wave system accuracy for static and dynamic tracking applications. Although definitive methods have yet to be established for 3D accuracy assessment in EMA systems, Kröger et al. (2008) and Yunusova, Green, and Mefferd (2009) have described initial efforts for the NDI Aurora and Carstens AG500 systems, respectively. Both studies presented accuracy estimates derived from rigid-body and human jaw-movement tracking experiments.

Kröger et al. (2008) used two 5-DOF sensors attached to a ruler at a fixed distance of approximately 20 mm apart. The ruler was moved manually by the experimenter, in time with a metronome, to simulate jaw movements with two speed and two amplitude variations. The method was designed to simulate slow and fast rate, large and small amplitude jaw wagging. Kröger et al. (2008) presented accuracy estimates in the form of *SD*s around the mean distance between sensors, demonstrating average measurement errors of < 1 mm for the NDI Aurora system. Average measurement errors and the magnitude of outlier (maximum) errors increased with the distance from the field generator and with average movement velocity. Comparable results are reported for jaw-movement tracking of a human subject producing head movement (“yes” and “no”) and brief speech tasks (slow and fast CV repetitions, phrase repetition, and passage reading).

Yunusova et al. (2009) presented spatial error estimates for movements of the Circal calibration device for the AG500 EMA system (Zierdt, 2007). The Circal device produces predictable rotations of sensors in the horizontal plane. The rotating plane has a diameter of 16 cm and requires approximately 1.5 min for a complete a rotation. Yunusova et al. (2009) also presented accuracy estimates derived from manual movements of two sensors (secured to a rigid body approximately 12.5 mm apart) and human jaw movements tracked during speech tasks. The rigid body was moved manually within a sphere of radius 15 cm, centered on the origin of the measurement field volume. Human jaw-movement data were derived from records of sustained phonation, syllable repetition, sentence repetition, and paragraph reading. Results were characterized by summary statistics for absolute deviations from the mean distance between sensors. In general, Yunusova et al. (2009) found median positional errors of approximately 0.5 mm or less for the AG500 system. A spatial resolution of 0.5 mm may be necessary to resolve perceptually salient speech-kinematic events (Perkell et al., 1992).

For the present study, three experiments were used to assess the NDI Wave: (a) tracking sensors affixed to a static rigid body positioned systematically at different locations within the electromagnetic field volume, (b) tracking sensors affixed to a dynamic rigid body (a four-bar linkage) following a repetitive path of motion and supported by a static framework positioned systematically at different locations within the electromagnetic field volume, and (c) tracking human jaw movements during speech. These data sets were used to estimate positional tracking error and variability of the NDI Wave system using known distance comparisons.

Method

Control of Rigid-Body Position

Rigid-body experiments required an adjustable surface to support systematic repositioning of the rigid bodies within the 3D electromagnetic field volume (Nafis, Jensen, & van Jako, 2008). A table with telescoping legs was constructed using polyvinyl chloride pipe and fittings, plywood, nylon fasteners (washers, nuts, and bolts), Velcro, and rubber chair-leg tips. The legs of the table base allowed for vertical adjustments at fixed 5-cm increments. The table top consisted of a sheet of 0.75-in. thick precision-planed glass mounted atop four rubber bumpers encasing 0.25-in. nylon nuts fastened on fixed 0.25-in. nylon bolts. Rotation of the rubber bumpers raised or lowered the vertical position. This mechanism allowed for fine height adjustment of each of the four corners of the table top through a continuous range of approximately 2.5 cm, facilitating precision positioning of the table and leveling of the horizontal surface. A 5-cm grid was drawn on poster board and secured to the superior surface of the glass table top. The grid was aligned by means of a T-square abutted against one edge of the glass and centered with respect to the NDI Wave field generator positioned along an adjacent edge of the glass. Two bull's-eye spirit levels were placed at various locations on the table top and field generator to assist with leveling. A 25-lb concrete block was placed on the middle (plywood) support shelf, and two 50-lb bags of sand were placed on the bottom support shelf as ballast to ensure stability of the table.

Static Tracking

The rigid body used in Experiment 1 was a metric engineer's scale with six 5-DOF sensors attached at approximate 1-cm intervals along a measurement surface oblique to the surface of the table. Because sensor orientation may affect tracking accuracy (Kröger et al., 2008), and orientation may be difficult to control in practical application, a fixed oblique (non-normal to the field generator surface) orientation of the sensors was thought to improve the validity of tracking error estimates by avoiding the implausibility of consistently optimal sensor orientation. All 5-DOF sensors assumed a fixed orientation with a roll of 50° relative to the horizontal surface. One 6-DOF sensor was affixed to the end of the scale and used in conjunction with the grid on the table surface as a reference for repositioning the rigid body at different locations within the plane defined by each vertical setting of the table.

The process of data acquisition involved first establishing the midpoint vertical position of the table by interactively adjusting the table height (and level) and the positioning of the NDI Wave field generator. Reference lines defining the horizontal and vertical middle axes of the field generator surface were drawn on the table using a T-square. The center of the field generator (intersection of vertical and horizontal lines) was aligned with the center line of the gridded surface. A triangular set square was used to ensure a normal relationship between the front surface of the field generator and the table surface. The position of the field generator was then secured using the mounting arm provided with the NDI Wave system. Sections of polyvinyl chloride pipe were also placed underneath the field generator to eliminate the possibility that it would oscillate if perturbed. Each record of data collection involved repeated repositioning of the rigid body at each grid intersection on the surface of the table.

At each table height setting, a data record was generated for each of four conditions: (a) 300-Ref condition (tracking all 5-DOF sensors with the 300-mm^3 field volume settings, with all positions encoded with reference to a local coordinate system origin defined by the position of the 6-DOF reference sensor); (b) 500-Ref condition (same as Condition 1, but using the 500-mm^3 field volume); (c) 300-No Ref (tracking all 5-DOF and the 6-DOF sensors in machine space, without the use of the automated head-movement correction algorithm); and (d) 500-No Ref condition (same as Condition 3, but using the 500-mm^3 field volume). A novel rigid-body position was defined at any place where the reference sensor was aligned with a grid intersection and all sensors on the rigid body where registered by the NDI Wave, as indicated on the real-time data display. This approach typically resulted in 30 different static positions of the rigid body for each 300-mm^3 data record and 90 different static positions for each 500-mm^3 data record.

To establish a basis for comparison of all data acquired during the experiment, a 30-s data record was collected with the table at the midpoint vertical position of the field generator. The rigid body was positioned such that all sensors were centered (along the anterior–posterior dimension) within the field, equidistant (100 mm) away from the field generator surface. Averaged across samples, data from this record were used to define the known distance between each adjacent sensor along the rigid body. All tracking error estimates were calculated with reference to these distances.

Dynamic Tracking

Experiment 2 followed the protocol used for static tracking except for the use of a different rigid body. A kinematic chain was constructed of Lego building blocks to systematically assess positional tracking error of the NDI Wave system in a dynamic application. The dynamic component of the model was defined by a four-bar linkage (crank-rocker mechanism) with 1 DOF (Vinogradov, 2000). The long bar of the linkage supported an 8-cm length of tongue depressor with six 5-DOF sensors placed along the length, approximately 1 cm apart. The tongue depressor was necessary because direct adhesion of the sensors to the Lego material proved unreliable. Thus, the tongue depressor was secured to the long bar of the linkage, and the sensors were secured to the tongue depressor. One 6-DOF sensor was secured to an anterior portion of the rigid framework to serve as a reference for repositioning the apparatus. The crank mechanism of the four-bar linkage was connected via a gear system to a 45-cm plastic axel driven by a precision drill motor (Model PD-3; OK International, Garden Grove, CA). The Lego model and drill motor were attached to a 0.75 × 7.25 × 48 in. oak plank. The relatively long driving axel and support plank allowed the entire apparatus to be repositioned anywhere on the adjustable table without the metal components of the drill motor entering the electromagnetic field volume and causing field distortion.

The dimensions of the four-bar linkage and gearing of the crank mechanism were defined to evoke sensor movements that roughly approximated characteristics of the kinematics of human speech (Perkell & Zandipour, 2002; Westbury, Severson, & Lindstrom, 2000). The kinematics of the crank-rocker mechanism caused different sensors to follow different characteristic movement trajectories with different peak and average movement speeds. The sensor closest to the crank mechanism followed the trajectory with the most rotational pattern and lowest average speed (89 mm/s), whereas the sensor closest to the rocker mechanism followed the trajectory with the most reciprocating pattern and highest average speed (137 mm/s). Sensors positioned between the most anterior and posterior ones followed intermediate trajectories that combined variously rotational and reciprocating patterns and produced intermediate average speeds. Across sensors, peak speeds averaged 260 mm/s. For citation form speech, Westbury et al. (2000) reported peak lingual speeds averaging 136 mm/s for the word *problem*. For syllable repetitions (diadochokinesis), Perkell and Zandipour (2002) reported peak lower lip closing speeds averaging as high as 290 mm/s.

With regard to sensor orientation, the dimensions of the crank-rocker mechanism evoked periodic variations in sensor pitch. The long bar of the mechanism traversed a 20° pitch range, moving between 17.5° and 37.5° below horizontal. Hoole and Nguyen (1999) suggested that a pitch range of 15° may be a reasonable estimate for variation in tongue-sensor orientation during conversational speech. Ostry, Vatikiotis-Bateson, and Gribble (1997) presented data that suggest speech ranges of variation in jaw pitch of 12° may increase to as much as 20° for some subjects during mastication.

Known Distance Measure

All positional tracking error estimates were calculated with reference to the known distance between adjacent 5-DOF sensors. Five discrete distance values between each adjacent pair of 5-DOF sensors were established for each of the two rigid bodies as described above. For each indexed data position, the difference between the five registered distances and the five known distances was calculated. The root-mean-square across these five comparisons served as the estimate of positional tracking error for each position within the field.

Speech-Tracking Protocol

Experiment 3 used speech-kinematic data from 10 human subjects. Six 5-DOF sensors were affixed to the tongue, lips, and jaws (two each), with a 6-DOF sensor affixed midsagittally between the eyebrows using Iso-Dent adhesive (Ellman International, Oceanside, NY). Subjects were seated with the left profile parallel to the surface of the field generator. The field generator surface was positioned approximately 5 cm from the left ear of each subject. Subjects completed a reading of the "Farm Passage" (Crystal & House, 1982). Only jaw-sensor data were used for estimating tracking error, as these sensors assumed fixed relative positions. For each subject, one sensor (MI) was secured to the labial surface of the juncture of the central mandibular incisors (midsagittal), and another sensor (MM) was secured to the buccal surface of the right first or second molar. Both sensors were positioned on the gingival tissue near the enamel–gingival border. Gingival tissue proved more reliable for sensor adhesion than enamel surfaces. A single known distance value between the MI and MM sensors was calculated from the average registered distance between the two jaw sensors over 10 s while each subject held a relatively stationary position of the mandible. Within the data record for each subject, all samples for which both jaw sensors were registered were used to estimate positional tracking error by comparison with the known distance value. All procedures involving the human subjects were approved by the Marquette University Institutional Review Board.

Results

Preliminary analyses revealed no differences between positional tracking with and without automated head-movement correction. Consequently, the Ref and No Ref conditions for all rigid-body data were pooled. Inferior–superior (vertical) position within the field also proved to have negligible influence on tracking error. Consequently, all data were pooled across vertical position. Table 1 and Table 2 present distributional summaries for data pooled across vertical position and organized by distance from the field generator surface for both field volume settings in static and dynamic tracking applications, respectively. Median, interquartile range (IQR), 95% quantile, and maximum values are shown. Data are organized in columns labeled by distance from the field generator surface. For example, in Table 1, the column labeled 50 presents distributional summary statistics for positions indexed at the border of the measurable field volume nearest the field generator surface. Comparison between the two field volume size settings suggests similar results for the middle of the error distributions (i.e., medians of 0.19 mm and 0.12 mm; IQRs of 0.22 mm and 0.21 mm) that are differentiated with respect to the larger upper error ranges for the 500-mm^3 volume. The Total column in each table indicates results across all distances for each field volume.

As a result of anatomical differences and variations in the ease of sensor positioning, the physical distance between sensors MI and MM varied across the 10 subjects (M = 38.75 mm; SD = 3.60 mm). Differences in mandibular girth in combination with variation in the

Table 1. Summary statistics for static positional error (in mm).

	Distance from field generator									
Value	**500**	**450**	**400**	**350**	**300**	**250**	**200**	**150**	**100**	**50**	**Total**
					500-mm^3 field						
Med	5.98	3.78	2.57	1.79	1.01	0.65	0.41	0.23	0.19	0.19	0.71
IQR	9.09	5.43	3.34	2.28	1.37	0.92	0.58	0.35	0.31	0.22	2.12
95%	21.57	13.28	8.28	5.11	4.09	2.75	1.68	1.15	0.88	0.76	8.92
Max	32.57	26.91	20.01	10.50	7.02	8.98	4.82	2.50	2.84	2.54	32.57
					300-mm^3 field						
Med				0.88	0.54	0.31	0.17	0.13	0.12	0.26	0.88
IQR				1.11	0.70	0.37	0.22	0.19	0.21	0.45	1.11
95%				3.27	2.12	1.46	0.56	0.57	0.46	1.83	3.27
Max				7.01	3.21	6.00	0.92	0.88	1.07	7.01	7.01

Note. Med = median; IQR = interquartile.

positioning of each subject resulted in differences between subjects in the average distance of MM from the field generator (M = 137.30 mm; SD = 21.00 mm). All subjects were able to comfortably maintain a position whereby MM (the most distal sensor) stayed within 200 mm of the field generator throughout data collection. Table 3 presents distributional summaries of jaw-tracking error estimates for the 10 subjects reciting the Farm Passage. Both median and IQR values fell below 0.25 mm for all subjects. Maximum errors were consistently approximately 1.0 mm or less for all subjects.

Discussion

The focus of this work was on quantifying the spatial resolution of the NDI Wave system. The data presented suggest that average tracking errors stay near or below 0.5 mm within approximately 200 mm from the field generator surface for both field volume settings. Tracking error control was improved using the 300-mm^3 field volume setting. The 500-mm^3 setting, in contrast, appeared to offer little useful additional field volume. Beyond 250 mm, median and IQR values consistently exceeded 1.0 mm, and outlier errors (> 2.0 mm) became more prevalent and extreme. The magnitudes of extreme tracking errors obtained with the NDI Wave system may exceed those reported for the Carstens AG500. On the basis of data presented by Yunusova et al. (2009), the AG500 system tracking error appears relatively more stable throughout the field volume when compared with the NDI Wave. This stability, however, is critically tied to a necessary, time-consuming user calibration process (Zierdt, 2007). The NDI Wave system, in contrast, requires no user calibration, making it more efficient to use.

In general, static tracking accuracy is modestly superior to dynamic tracking for the NDI Wave system.

Table 2. Summary statistics for dynamic positional error (in mm).

	Distance from field generator									
Value	**500**	**450**	**400**	**350**	**300**	**250**	**200**	**150**	**100**	**50**	**Total**
					500-mm^3 field						
Med	8.50	5.79	4.48	3.05	1.73	1.11	0.61	0.31	0.22	0.16	1.16
IQR	11.73	9.07	6.24	4.20	2.53	1.76	0.97	0.67	0.42	0.32	3.79
95%	28.41	22.41	17.10	12.35	7.33	4.76	3.18	1.89	1.36	1.16	14.73
Max	66.64	50.13	51.01	30.45	23.16	11.75	9.98	7.99	4.09	3.86	66.64
					300-mm^3 field						
Med					1.29	0.63	0.27	0.31	0.07	0.08	0.21
IQR					1.69	0.78	0.42	0.19	0.09	0.13	0.57
95%					4.62	2.00	1.09	0.62	0.29	0.52	2.31
Max					9.12	2.85	3.50	1.10	4.28	2.19	9.12

Table 3. Summary statistics for jaw movements during speech (in mm).

	Subject									
Value	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Med	0.18	0.08	0.03	0.06	0.09	0.11	0.09	0.08	0.13	0.16
IQR	0.22	0.09	0.04	0.08	0.11	0.15	0.11	0.11	0.10	0.16
95%	0.55	0.22	0.08	0.19	0.28	0.37	0.26	0.24	0.37	0.48
Max	1.03	0.43	0.27	0.56	0.78	0.92	0.64	0.55	0.83	1.06

This conclusion is valid only within the current experimental constraints (i.e., the orientations and relative sensor positions studied). Relatively superior static tracking accuracy is of little practical significance for speech-kinematic applications because dynamic tracking is necessary.

Dynamic tracking results were obtained using a rigid four-bar linkage with 1 DOF. Although the changing speeds and orientations of the sensors attached to the model may roughly approximate those measured for human articulator movements, the fixed distances between adjacent sensors and limited variability in sensor trajectories limit the extent to which the modeling results can be generalized to human articulator-movement tracking.

On the basis of the model data, dynamic tracking within the near field (< 200 mm) can be characterized by positional tracking errors that tend to be < 0.5 mm. This portion of the field is particularly pertinent, as anthropometric data indicate that average human head breadth is 152 mm (Gordon, 1996). The portion of the field within which sensor positions can be resolved begins 50 mm from the field generator surface. Thus, the useable near field within which tracking error can be reasonably controlled at < 0.5 mm is approximately 150 mm wide. Midsagittal sensor placement, with the subject's profile facing the field generator, is likely to assist in maintaining equivalent error rates across sensors. The 150-mm width of the optimal tracking volume of the system also allows sufficient buffer to ensure that sensors that cannot be positioned midsagittally, such as a second molar sensor, still fall within the optimal volume. An important consideration is that human subjects not be positioned too closely to the field generator because, according to the manufacturer, field characteristic within the first 20 mm of the field generator surface (outside of the working field volume) exceed maximum permissible exposure rates for human subjects (Institute of Electrical and Electronics Engineers, 1999).

The results of Experiment 3 suggest that tracking accuracy for human jaw movements during paragraph reading may be modestly superior to tracking of the dynamic model, particularly with regard to the frequency and magnitude of errors of > 0.5 mm within the near field. This apparent improvement in human application is likely influenced by slower sensor speeds and smaller ranges of variation in sensor orientation in the human data compared with the model. Another potentially pertinent factor that has not been addressed in this study is differences in the distance between adjacent sensors within the field. For the model, the distance between adjacent sensors is constant at approximately 1 cm. For the human data, this distance varies somewhat across subjects but approaches 4 cm on average. Interaction between adjacent sensors is one of several possible sources of tracking error (see Perkell et al., 1992). This potential source of error has yet to be systematically investigated for the NDI Wave system.

In summary, dynamic tracking accuracy was superior for the 300-mm^3 field (compared with the 500-mm^3 field) of the NDI Wave system. Tracking accuracy did not vary significantly along the anterior–posterior and inferior–superior dimensions of the field and did not appear to be influenced by use of the automatic head-movement correction settings. Although extreme tracking errors (> 2 mm) did occur within the near field of the 300-mm^3 volume, these errors occurred in < 1% of samples. Within the near field of the 300-mm^3 volume, 88% of dynamic positional errors were < 0.5 mm and 98% were < 1.0 mm. Human jaw tracking for 10 subjects during paragraph reading revealed tracking errors that were typically < 0.5 mm. Taken together, these results suggest that tracking accuracy for the NDI Wave system may be bolstered by using the 300-mm^3 volume setting and positioning subjects so that sensors stay within 200 mm of the field generator surface. Future studies need to systematically assess the impact of factors such as sensor orientation and intersensor distance on tracking accuracy.

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