Temporal-spatial reach parameters derived from inertial sensors: comparison to 3D marker-based motion capture

Original Article

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Abstract

Reaching is a well-practiced functional task crucial to daily living activities, and temporal-spatial measures of reaching reflect function for both adult and pediatric populations with upper-extremity motor impairments. Inertial sensors offer a mobile and inexpensive tool for clinical assessment of movement. This research outlines a method for measuring temporal-spatial reach parameters using inertial sensors, and validates these measures with traditional marker-based motion capture. 140 reaches from 10 adults, and 30 reaches from nine children aged 18-20 months, were recorded and analyzed using both inertial-sensor and motion-capture methods. Inertial sensors contained three-axis accelerometers, gyroscopes, and magnetometers. Gravitational offset of accelerometer data was measured when the sensor was at rest, and removed using sensor orientation measured at rest and throughout the reach. Velocity was calculated by numeric integration of acceleration, using a null-velocity assumption at reach start. Sensor drift was neglected given the 1-2 seconds required for a reach. Temporal-spatial reach parameters were calculated independently for each data acquisition method. Reach path length and distance, peak velocity magnitude and timing, and acceleration at contact demonstrated consistent agreement between sensor- and motion-capture-based methods, for both adult and toddler reaches, as evaluated by intraclass correlation coefficients from 0.61-1.00. Taken together with actual difference between method measures, results indicate that these functional reach parameters may be reliably measured with inertial sensors.

Introduction

Temporal-spatial measures of the upper extremity reflect function in many populations with motor impairments such as stroke, Parkinson's, cerebral palsy (CP), and developmental coordination disorder (DCD). CP, defined as disorders of movement and posture arising from non-progressive brain injury around the time of birth, and DCD, a milder motor impairment often equated with clumsiness, can both

result in impaired upper-extremity function in pediatric populations (*DSM-IV-TR Diagnostic and Statistical Manual of Mental Disorders*, 2000; Rosenbaum et al., 2007). These impairments can be quantified by the temporal-spatial parameters of reaching. Reaching is a well-practiced functional task used in feeding, grooming, and otherwise interacting with the world during daily life, and approaches adult-level consistency by the end of the second year (Berthier and Keen, 2006). Children with CP tend to have longer reach times, less efficient paths to the target, higher velocities at contact with the target, later peak velocities, and more movement units—a measure of reach smoothness defined as the number of times the wrist speeds up and slows down during a movement—than their typically-developing peers (Butler et al., 2010; Chang et al., 2005; Rönqvist and Rösblad, 2007; van der Heide et al., 2005). While the literature on reaching in children with DCD is less extensive, they have been found to demonstrate longer times to complete a movement and altered timing of peak velocity (Johnston et al., 2002; Smyth et al., 2010). Identifying and quantifying reach impairment is valuable because treatments have successfully helped children decrease movement time and improve path efficiency and smoothness (Fetters and Kluzik, 1996; Kluzik et al., 1990). Currently, quantitative reach evaluations typically occur in dedicated 3D marker-based motion capture laboratories.

Motion data from lightweight, wearable inertial sensors have great promise in applications of robotics, virtual reality training, games, and biomedical engineering—including motion analysis. While traditional marker-based motion capture requires more than \$150,000 initial investment and a dedicated space, inertial sensors cost about \$50 each, orders-of-magnitude less expensive than optical-based systems. An affordable, highly-mobile motion laboratory could greatly enhance the global participation of researchers currently under- or unrepresented in motion research due to limited availability of geographically-sparse motion labs, and the high initial cost of developing a lab. If applied to clinical gait and upper-extremity analysis, an inexpensive, mobile motion lab could bring motion analysis to the clinic, and increase access to poor, underserved, or rural families. In addition, inertial sensors do not

suffer from issues of occlusion, which are particularly prevalent in populations of very young children, who are most comfortable (and most likely to comply with assessment) when in close contact with a parent.

Temporal-spatial reach parameters and their functional significance have not been explored in toddlers. The quality of toddler hand and finger movements have been reported during reaching-to-grasp, including whether and when the hand opens in anticipation of the object, whether the shape of the hand anticipates the shape of the object, and the quality of the grasp (Bennett and Castiello, 1994). However, the reach itself has not yet been quantitatively analyzed; objectively-measured position, velocity and acceleration parameters may add to the current approaches for understanding toddler reach, as they have in older children and adults. If accurate, inertial sensors could be a valuable tool for quantifying reach in both typically-developing and high-risk toddlers.

Inertial measures are limited by drift over time, which compounds with each integration. Mitigating drift requires frequent sensor recalibration. Recently, investigators validated velocity and position estimates calibrated with known initial conditions at null-velocity points in the stance phase of gait (Mariani et al., 2010; Peruzzi et al., 2011). The present research outlines a method for processing inertial sensor measures of upper-extremity reaching with null-velocity stages, and validates these measures with traditional marker-based motion capture in adult and toddler populations.

Methods

In this research, motion during reaching was simultaneously measured using two methods: traditional 3D marker-based motion capture (“motion capture”) and inertial sensors (“sensors”). In addition,

reaches were captured on high-speed video (239.76 frames/s). At the beginning of the testing session, a pen with a 3D reflective marker fixed to it was used to strike an inertial sensor, creating a detectable synchronizing event on all three media: motion capture, sensors, and video. Following the pen strike, the sensor was flipped over to generate an inertial signal, making general timing of the strike easily-identifiable for that medium. Because of the short timescale of the event (initial strike occurred on a single video frame, $< \sim 1/240$ sec), this event's identification allowed time synchronization of the different methods. Timing of reach start and initial contact with the target object was identified on video, then calculated for motion capture and sensors.

Participants

10 adults and 14 typically-developing toddlers were recruited from the community. Adults completed a full reach-and-grasp cycle, starting with elbows flexed 90 degrees and the target object at 75% of maximum reach, as described previously (Butler et al., 2010); however, only the first phase of reaching was analyzed in this study. Toddlers reached for a cube: parents cupped their hands over their child's on the edge of the table, with the child's elbows bent comfortably at approximately 90 degrees, and released the child's hands according to a verbal cue after the investigator placed the cube at approximately 75% of maximum reach. The cube is a standard red cube from a Bayley Scales of Infant Development-3rd Edition kit, decorated with sparkly stickers to increase its attractiveness as a target. All participants were either right-handed or demonstrated no preference.

Reach temporal-spatial parameters

Reach time was calculated from event identification on the video. Reach distance, path length, index of curvature, velocity at contact, peak velocity, time to peak velocity, percent reach time to peak velocity,

acceleration at contact, peak acceleration, time to peak acceleration, and percent reach to peak acceleration were calculated independently based on motion capture and inertial sensor data. The index of curvature is the ratio of reach path length to reach distance, and indicates efficiency of the reach.

Motion Capture

Reflective markers were fixed on the top of the inertial sensor, which was fixed to the top of the wrist with a sticker (adults) or small elastic band (toddlers). Two equivalent marker sets were used: three reflective markers of ½ inch diameter were fixed to three corners of the sensor and used to create a virtual fourth marker at the centroid of the sensor face, or one reflective marker of ¾ inch diameter was fixed directly on the centroid of the sensor face. The centroidal marker, whether virtual or physical, was thus equivalent for both marker sets, and was exclusively used for all parameter calculations, which were derived entirely from translational rather than rotational kinematics. Three-dimensional position data were recorded at 100 Hz from an eight-camera system, and filtered with a fourth-order zero-lag 6 Hz Butterworth filter (Motion Analysis Corporation, Santa Rosa, CA). Velocity and acceleration data were calculated from the numeric derivative of the position data. Temporal-spatial reach parameters were calculated with a custom MATLAB program.

Inertial Sensors

Inertial sensors with three-axis accelerometers, gyroscopes, and magnetometers (APDM, Inc., Portland, OR), were fixed to the top of the wrist. Inertial sensors weighed 22 grams and measured 48.5x36.5x13.5 mm. Data were recorded at 128 Hz; trials in which sensors were bumped or dislodged were identified on high-speed video and excluded. Orientation data in the form of quaternions are calculated from accelerometer, gyroscope, and magnetometer data according to APDM's proprietary algorithm. Accelerometers have an offset caused by gravity; this offset must be calculated and removed throughout a reach in order to determine acceleration of the wrist, and thus motion of the reach.

Acceleration recorded when the sensor is at rest is due exclusively to gravity; combined with the orientation of the sensor at that point, the constant offset due to gravity can be calculated and removed for all time points, assuming that the relative orientation of the sensor is known for all times, elucidated below.

$$[\mathbf{g}\text{-free Acceleration}]_B = [\mathbf{Raw acceleration}]_B - [\mathbf{g}]_B$$

Where $[\mathbf{g}]_B$, the force of gravity in a reference frame fixed B on the sensor, is given by:

$$[\mathbf{g}]_B = {}^B R^N [\mathbf{g}]_N = ({}^N R^B)^{-1} [\mathbf{g}]_N$$

Where $[\mathbf{g}]_N$ is the force of gravity in reference frame N fixed in the room, defined by the raw acceleration at an identified point of rest (i.e., when all measured acceleration is due to gravity). ${}^N R^B$ is the rotation matrix relating the orientation of reference frame N to reference frame B, given by (Mitiguy, 2015):

$${}^N R^B = \begin{bmatrix} 2\varepsilon_1^2 + 2\varepsilon_0^2 - 1 & 2(\varepsilon_1\varepsilon_2 - \varepsilon_3\varepsilon_0) & 2(\varepsilon_1\varepsilon_3 + \varepsilon_2\varepsilon_0) \\ 2(\varepsilon_1\varepsilon_2 + \varepsilon_3\varepsilon_0) & 2\varepsilon_2^2 + 2\varepsilon_0^2 - 1 & 2(\varepsilon_2\varepsilon_3 - \varepsilon_1\varepsilon_0) \\ 2(\varepsilon_1\varepsilon_3 - \varepsilon_2\varepsilon_0) & 2(\varepsilon_2\varepsilon_3 + \varepsilon_1\varepsilon_0) & 2\varepsilon_3^2 + 2\varepsilon_0^2 - 1 \end{bmatrix}$$

Where ε_i are ${}^N \varepsilon_i^B$, quaternions defining the orientation of sensor B in room N, calculated with: the quaternions output by the sensor during the rest period, ${}^C \varepsilon_i^N$, giving the orientation of the room N in a compass-based reference frame C; and the quaternions output by the sensor during data collection, ${}^C \varepsilon_i^B$, giving the orientation of the sensor B in the compass-based reference frame C. Quaternions ${}^N \varepsilon_i^B$ may be calculated from ${}^C \varepsilon_i^N$ and ${}^C \varepsilon_i^B$ according to known quaternion math (Mitiguy, 2015).

However, sensor readings are not consistent throughout time and tend to drift; therefore, rather than using a single recording of the sensor at rest for gravity-cancellation calculations, a time when the sensor is at rest must be identified within a few seconds of each reach. This identification must be done manually for each reach, and the resultant g-free acceleration calculated and examined for accuracy.

Sensor errors, whether due to drift or magnetometer data (which can be affected by the environment) are often obvious at this point. Although some inertial sensors do not use magnetometers, they are essential for orientation data. Normal drift should not render data unusable over the time scale of a normal reach, approximately one second. However, major errors from damaged sensors, bad calibration, or magnetic interference, can render data inaccurate even for short time scales.

Following correction of acceleration data for gravity, velocity can be calculated with a known value (for example, initial value). Therefore, it is important for reaches to begin at rest; initial velocity is assumed to be zero. The null-velocity assumption allows velocity calculation from numeric integration, and has been shown to be accurate for swing phase of gait (Peruzzi et al., 2011). Due to drift, numeric integration is a notoriously inaccurate calculation for inertial sensors; however, it may be possible to obtain accurate results on small time scales, such as during a one-second reach or gait cycle, when drift has not compounded enough to compromise data's usefulness (Mariani et al., 2010; Peruzzi et al., 2011). Position data are calculated from double numeric integration, and thus at higher risk of error and should be interpreted cautiously.

Temporal-spatial reach parameters were calculated from a custom MATLAB program.

Statistics

Temporal-spatial reach parameters calculated using sensors and motion capture were compared, adults separately from toddlers. Actual difference, sensor-based value minus motion-capture-based value, was calculated for each parameter of each reach, as well as average value for each parameter. These results were used to create Bland-Altman plots; average value was used for the x-axis, rather than motion-capture or sensor values, because it is not clear that one method is an absolute gold standard (for

example, motion capture may be more accurate for position measures, while sensors may be more accurate for acceleration measures) (Bland and Altman, 1986; Rankin and Stokes, 1998). Single-measures consistency intraclass correlation coefficients (ICC), an index for reliability of multiple measurements, were calculated for the sensor-based compared to motion-capture-based measures of each parameter, in both adults and toddlers (Bartko, 1966; Rankin and Stokes, 1998).

Results

10 adults (mean age 29.7 years) performed 140 reaches total, and nine toddlers (mean age 19.6 months) performed 30 reaches total, which qualified and were characterized. Five of the 14 toddlers recruited were excluded due to noncompliance (two) or error in conducting the test (video recording (one); sensor recording (one); and striking the sensor outside the video view (one)). All reaches analyzed were right-handed.

Table 1 reports the ICC for each parameter, the average difference between sensor-based and motion-capture-based measures (sensor minus motion capture), and the average parameter value, for adult and toddler reaches separately. Landis and Koch provided guidelines for interpreting ICCs as follows: < 0.00 Poor; 0.00-0.20 Slight; 0.21-0.40 Fair; 0.41-0.60 Moderate; 0.61-0.80 Substantial; and 0.81-1.00 Almost Perfect (Landis and Koch, 1977). According to this interpretation, agreement between methods was “substantial” or “almost perfect” for reach path length, reach distance, peak velocity and its timing, and acceleration at contact in both adults and toddlers. Agreement was “substantial” or “almost perfect” in adults, but not in toddlers, for peak acceleration; the reverse was true for timing of peak acceleration, which demonstrated “substantial” or “almost perfect” agreement in toddlers but not adults. The highest agreement occurred in peak velocity and its timing and acceleration at contact; the lowest agreement occurred in index of curvature and velocity at contact.

Systematic differences between measurement methods are generally small compared to the parameter value, including in reach path length and distance (errors ≤ 0.9 cm for adults and toddlers for distances of 13.1-24.2 cm), peak velocity (-0.7 cm/s error for 48.5 cm/s mean in adults, -0.6 cm/s error for 45.9 cm/s mean in toddlers) and its timing (<0.01 s error for adults and toddlers over 0.45-0.55 s reaches), and acceleration at contact (<0.01 m/s² error for 0.66 m/s² mean in adults, -0.12 m/s² mean for 2.33 m/s² mean in toddlers). However, errors were relatively large for velocity at contact (7.9 cm/s error for 11 cm/s mean in adults, 6.6 cm/s error for 30.9 cm/s mean in toddlers), peak acceleration (0.32 m/s² error for 2.70 m/s² mean in adults, 1.54 m/s² mean for 4.9 m/s² mean in toddlers) and its timing in toddlers (-0.06 s error for 0.31 s mean).

Information on parameter differences is visualized and expanded upon in Figures 1 and 2, Bland-Altman plots of selected reach parameters for adults and toddlers, respectively. For adults, path length and reach distance show larger sensor-based values relative to motion-capture-based values as the mean value increases; this trend is less evident in toddlers, but may still be present. In adults, peak velocity show tight agreement, while velocity-at-contact error increased as mean value increased, though not in a specific direction. In toddlers, a relationship with mean value is not evident, although errors are larger overall. Acceleration at contact and peak acceleration measures both appear to be in greater agreement for adults than toddlers, although peak acceleration error appears to increase with increasing mean value in both groups. There is one toddler reach which appears to be an outlier in both mean value and errors, and may not be representative of typical measure method agreement.

Discussion

Sensor-derived compared to motion-capture-derived measures of most temporal-spatial reach parameters were found to be consistent. Reach path length and distance, peak velocity magnitude and

timing, and acceleration at contact all demonstrated ICCs in the “substantial” to “almost perfect” range for both adults and toddlers. Peak acceleration timing, but not magnitude, were also in this range for toddlers, while the reverse was true for adults. Magnitudes of the differences between measurement methods (systematic differences) were relatively small compared to mean values, specifically for reach path length and distance, peak velocity magnitude and timing, and acceleration at contact: these results complement the ICC assessment (random differences). ICC and measures of actual difference also tell a concordant story for velocity at contact, this time of poor agreement between sensor-based and motion-capture-based methods. Peak acceleration appeared consistent for adults but not toddlers, for whom peak acceleration errors were both more variable and systematically higher for sensor-based versus motion-capture-based measures.

Index of curvature demonstrated very small actual differences between methods, yet had the lowest ICCs for both adult and toddler reaches, of .308 (“fair”) and .435 (“moderate”), respectively. This apparent disparity is explained by errors that are distributed evenly about zero—that is, sometimes sensor-based values are larger than motion-capture-based, and sometimes the reverse is true, but actual agreement is not good (systematic differences are low while random differences are low). Index of curvature is the ratio of total reach distance and reach path length; thus, it compounds errors from double-integrating sensor acceleration, and it is therefore not surprising to find index of curvature less reliable than reach distance or path length individually.

These findings suggest that the method described in this research can provide an accurate clinical assessment of reach, using mobile and inexpensive inertial sensors. Specifically, reach path length and distance, peak velocity magnitude and timing, and acceleration at contact were highly consistent between sensor-based and motion-capture-based methods. Index of curvature and velocity of contact

were least reliable, while peak acceleration and its timing have inconsistent results and require further investigation and development.

Disagreement between methods was greatest for velocity at contact, primarily due to the most common error seen in sensor-based velocity profiles of reach, a rise near the end of reach, as demonstrated in Figure 3 a-b and d-e. This error occurred to varying degrees in most reaches, although it can appear in some reaches but not others for the same person in the same reaching session, for reaches completed only seconds to minutes apart. Figure 3 c and f compare measures of velocity at contact for both sensor and motion capture; it appears that sensors may produce overestimates of velocity when velocity is very low, which may explain the lower agreement observed in adults, who have slower velocities at impact due to mature reaching patterns. Peak velocity, which occurs earlier in reach and has greater magnitude than velocity at contact, had excellent agreement between methods. Velocity at contact was generally higher in toddlers than adults, but was also subject to the end-of-reach rising-velocity error and had only marginally better agreement.

Conclusion

Temporal-spatial parameters of upper limb reaching based on inertial sensors were achieved by successful elimination of gravitational confound, as evidenced by the highly-consistent temporal-spatial measures derived from inertial sensors, compared to 3D marker-based motion capture in both adults and toddlers. Sensor measures of reach path length and distance, peak velocity magnitude and timing, and acceleration at contact demonstrated consistent agreement with the same measures derived from motion capture. Sensor measures of velocity at contact and index of curvature were inconsistent for

both adult and toddler reaches. Peak acceleration may be reliable in adults but not toddlers, although the influence of an outlier toddler reach is unclear; timing of peak acceleration appeared more consistent for toddlers. Examination of relationships between sensor-based peak acceleration magnitude and timing with function may clarify whether these parameters are sufficiently accurate for clinical relevance. Ultimately, several parameters of reach related to function may be reliably detected with inertial sensors.

Conflict of interest statement

The authors have no financial or personal relationships with other people or organizations that could inappropriately influence this work. Study sponsors had no role in the study design, the collection, analysis or interpretation of data, the writing of this manuscript, or the decision to submit for publications.

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Table 1: Comparison of sensor-based and motion-capture-based parameters for adults and toddlers, including mean parameter difference between methods (sensor-based minus motion-capture-based), mean parameter values, and single-measures intraclass correlation coefficient (ICC).

Parameter	Adult reaches (n=139)		Toddler reaches (n=30)	
	ICC	Difference (Mean value)	ICC	Difference (Mean value)
Reach path length	.804	0.9 cm (24.2)	.812	0.9 cm (15.6)
Reach distance	.715	-0.3 cm (21.7)	.621	0.9 cm (13.1)
Index of curvature	.308	0.06 (1.12)	.435	0.00 (1.20)
Velocity at contact	.464	7.9 cm/s (11.3)	.575	6.6 cm/s (30.9)
Peak velocity	.946	-0.7 cm/s (48.5)	.815	-0.6 cm/s (45.9)
Time to peak velocity	.984	0.00 s (0.55)	.951	0.00 s (0.45)
Percent reach time to peak velocity	.974	-0.5% (53.5)	.694	0.2% (67.7)
Acceleration at contact	.914	0.00 m/s ² (0.66)	.825	-0.12 m/s ² (2.33)
Peak acceleration	.841	0.32 m/s ² (2.70)	.580	1.54 m/s ² (4.9)
Time to peak acceleration	.535	-0.02 s (0.39)	.940	-0.06 s (0.31)
Percent reach to peak acceleration	.532	-2.7% (38.2)	.720	-10.7% (44.4)

Figure Captions:

Figure 1: Bland-Altman plots for reach parameters in adults. The mean of the sensor-based and motion-capture-based value for each reach (x-axis) is plotted against the difference between the sensor-based and motion-capture-based value for that reach (y-axis). Solid horizontal lines represent the mean difference between sensor-based and motion-capture-based values for all reaches; dashed horizontal lines represent ± 1.96 SD of the difference.

Figure 2: Bland-Altman plots for reach parameters in toddlers. The mean of the sensor-based and motion-capture-based value for each reach (x-axis) is plotted against the difference between the sensor-based and motion-capture-based value for that reach (y-axis). Solid horizontal lines represent the mean difference between sensor-based and motion-capture-based values for all reaches; dashed horizontal lines represent ± 1.96 SD of the difference.

Figure 3: An example of an adult's reaches in which one presents with velocity-at-contact error (a) and one does not (b), as well as a toddler's reach with the error (d) and without (e). Scatter plots of velocity at contact and peak velocity for adult (c) and toddler reaches (f).

Figure 1

Adult Bland-Altman plots

Figure 2

Toddler Bland-Altman plots

Figure 3

Adult

Adult

Toddler