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RESEARCH ARTICLE

Evidence of early development of action planning in the human foetus: a kinematic study

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Abstract The aim of the present study was to investigate whether foetal hand movements are planned and how they are executed. We performed a kinematic analysis of hand movements directed towards the mouth and the eyes in the foetuses of eight women with normally evolving pregnancies. At 14, 18 and 22 weeks of gestation, eight foetuses underwent a 20-min four-dimensional-ultrasound session. The video recordings for these movements were then imported into in-house software developed to perform kinematic analysis. We found that spatial and temporal characteristics of foetal movements are by no means uncoordinated or unpatterned. By 22 weeks of gestation the movements seem to show the recognizable form of intentional actions, with kinematic patterns that depend on the goal of the action, suggesting a surprisingly advanced level of motor planning.

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Introduction

Foetal movements have been extensively described, (Prechtl 1997; DiPietro 2005), however, only a gross interpretation of a crude trace for patterns, which indicate particular types of movement, has been provided. Little is known about how these movements are planned and how they are executed in the various stages of foetal development.

The principal source of existing knowledge about the development of foetal motor behaviours has been real-time ultrasound with on- or off-line analyses (e.g., Patrick et al. 1982; de Vries et al. 1988). Typically, these studies rely on observation periods of 60 min or longer. For instance, de Vries et al. (1985) have characterized the onset of various spontaneously generated movement patterns in the foetus from 7 to 19 weeks of gestational ages. During the first week they noticed that the onset of general movements of the head, trunk, and extremities occurred by 8.5–9.5 weeks and that foetuses were active for about 14% of a 60 min viewing period. By 14–19 weeks, foetuses were very active and the longest period without general movements was 5–6 min. In contrast, various authors have noticed a decrease in the number of generalized movements per hour from 16 to 32 weeks (Natale et al. 1985) and in the percentage of time during viewing in which movements were presented (de Vries et al. 1988). Therefore, it appears that spontaneous body movements begin by the end of the second month of gestation, increase in incidence around the end of the first trimester and before the end of second trimester gradually decrease until term.

Although the above studies have provided the basis for existing information on qualitative features of foetal movements and detection of specific behaviours, there are no reports of a kinematic-type analysis in uterus, which is rather common in infant studies (von Hofsten 1979). Kinematic analyses would contribute greatly to our understanding of motor development in the foetus as it has done for infant motor control with particular reference to the issue of how upper limbs movements are planned and controlled.

Little is known about the kinematic pattern of arm movements before purposeful reaching movements emerge. For instance, studies have found that pre-reaching patterns are characterized by multiple actions per mininute, and this occurs independently from the presence or absence of an external stimulus (Piek and Carman 1994; Thelen 1979). Other evidence suggests that the number of forward directed movements increases in infants as young as a few days when a toy is presented than when no toy is in view (von Hofsten 1982; Bhat et al. 2005; Bhat and Galloway 2006).

The transition from pre to spontaneous purposeful reaching movements is a fundamental aspect to understand reaching development. As reported, in the weeks preceding the initiation of reaching changes in spatial and temporal characteristics of arm movements are noticed. For instance, there is a tendency for arm movements to be directed more in the midline of the body from birth to the first week of reaching (Galloway and Thelen 2003; Lew and Butterworth 1997). Furthermore, the 'midline' effect becomes particularly evident when a toy was presented in the midline position (Galloway and Thelen 2003; von Hofsten 1984; Bhat et al. 2005; Bhat and Galloway 2006). The presence of a toy affects not only spatial characteristics of movement, but also movement frequency. Closer to the first week of reaching, infants moved their arms more frequently (Galloway and Thelen 2003; von Hofsten 1984; Bhat et al. 2005; Bhat and Galloway 2006) in the presence of a toy.

From the pioneering research of von Hofsten (1979, 1991), we know that the broad outlines of the developmental changes in infant hand trajectories as they learn to reach. Infants first reach consistently at about 3–4 months of age. In the first month, their reaching is inaccurate and shows poor control of hand trajectory, with characteristic jerky and zigzag movements. Such movements are identified kinematically as multiple segments of acceleration and deceleration or "movement units" (von Hofsten 1979). With age, reaching patterns of infants become straighter and more directly aimed towards the target and show fewer movement units. In addition, as the number of movement units decreases, the first movement unit occupies a larger proportion of the reach, so that one acceleration and deceleration brings the hand close to the target, followed perhaps by a small correction (von Hofsten 1979; Halverson 1931). Moreover, within the movement unit, investigators have found a relation between the speed of the movement and its curvature, with speed valleys associated with curvature peaks (Fetters and Todd 1987; Mathew and Cook 1990).

In the present study, we capitalize on the above mentioned studies to use kinematic techniques to investigate foetal upper limb movements. In particular, we raise the issue of the foetus reaching development by looking at the role played by the characteristics of the target on the planning of the velocity profile phases and spatial trajectories.

Our central question is not just how foetuses control spontaneous upper limb movements but whether during different gestational ages they modulate their particular patterns and coordination preferences with respect to the end-goal of the action. We address this question performing the kinematic analysis of upper limb movements directed towards different parts of the face (the mouth and the eyes; see Fig. 1) in eight foetuses during three different periods of their evolution (14, 18 and 22 weeks of gestation).

Our prediction is that there would be non-functional hand movements in the early foetal period. Therefore, during development the foetus would acquire motor skills which reflect an "environment specific" maturation similar to that shown during post-natal development in terms of pre and reaching phases (Bhat et al. 2005; Bhat and Galloway 2006). We would expect to see a kinematic patterning which is related to the end goal (i.e., the mouth and the eye). This differential kinematic patterning would suggest some development in motor behaviour and an increased level of motor control in the foetus. In line with this prediction our core results are that spatial and temporal characteristics of foetal movements are by no means uncoordinated or unpatterned. They show kinematic patterns that seem to depend on the goal of the action, suggesting some level of action planning.

Materials and methods

Subjects

The eight women with a singleton pregnancy who participated in this study were a convenient sample of low-risk pregnant women attending the Institute of Child Health IRCCS Burlo Garofolo (Table 1). All future mothers gave written informed consent and approval. The designation of "low risk" for foetuses was made during the initial obstetric visit based on maternal medical history and checked at each subsequent visit by the gynaecologist. Each of the eight foetuses was studied longitudinally at 14, 18 and 22 weeks of gestation and underwent a 20-min four-dimensional-ultrasound (4D-US) session at each observation. The data of the foetuses are reported in Table 2. The experimental procedures were approved by the Institutional Review Board at the Institute of Child Health IRCCS Burlo Garofolo and were in accordance with the declaration of Helsinki.

Procedure

Each woman was identified by the prenatal sonologist during her first visit at 12 weeks of pregnancy and foetal age was calculated comparing the mother's last menstruation date and the measurements of the foetus (Crown Rump Length) taken during the ultrasound examination. Upon the couple's agreement to take part in this study, the appointment for the first ultrasound imaging was fixed during the 14th week. The following appointments were within the 18th and 22nd week. At the end of each video recording the humeral length was measured and later used in the kinematic analysis. Each examination was conducted in the early afternoon, 2 h after lunch. The images were obtained with the future mother in a semi-recumbent position, with diminished light, consistent with clinical obstetrical imaging. Each woman was interviewed prior to ultrasound imaging to record any environmental changes in work or family conditions (i.e., stress that could possibly affect the movement of the foetus) that she may have perceived over the preceding 4 weeks. She was also asked to complete two questionnaires involving both perceived state anxiety and trait anxiety, which always resulted within normal range.

Instrumentation

For the purpose of this study we analyzed the abdominal four dimensional ultrasound (that is 3D images in time known as 4D-US; Voluson 730 Expert by GE Medical Systems) of eight foetuses. The ultrasound technique allows the change of several parameters: depth of the visual field, the sweeping angle that defines the sample volume and the frame rate. These parameters have a direct relationship to each other. In this study the machine was set at the fixed frame rate of 4 Hz, to guarantee the same numbers of images per second. The crystal array of the transducer swept mechanically over the volume of the uterine cavity, framing the defined regions of interest. To visualize the

Table 1 Characteristics of the mothers involved in the study

Mothers	Age	Education	SES	BMI	Smoker	BP	AF	Dating
1	33	High School	Secretary	0.33	Stopped smoking	110/70	Normal	US
2	37	High School	Secretary	0.34	Stopped smoking	110/70	Normal	US
3	28	Junior High School	Masseuse	0.32	No	120/80	Normal	US
4	27	High School	Secretary	0.46	No	145/85	Normal	US
5	28	BA	MD	0.34	No	110/70	Normal	US
6	39	BA	Laboratory technician	0.39	No	120/80	Normal	US
7	30	Junior High School	Barperson	0.33	No	120/80	Normal	US
8	27	High School	Store clerk	0.38	Stopped smoking	100/70	Normal	US

SES social economical status, *BMI* body mass index, *BP* blood pressure, *AF* amniotic fluid

Table 2 Birth data for the eight foetuses

Fetuses	BGA	Sex	Apgar first minute	Apgar fifth minute	BW (g)	BE	pH	NE	F. Pos	Placenta
1	39 + 4	F	10	10	3810	− 4.5	7.22	Normal	Cef	Anterior
2	41 + 2	F	10	10	2810	NA	NA	Normal	Cef	Anterior
3	39 + 5	F	9	10	3110	NA	NA	Normal	Cef	Anterior
4	41 + 6	M	9	10	2800	− 9	7.16	Normal	Cef	Posterior
5	40 + 3	M	9	10	3350	− 5.2	7.19	Normal	Cef	Posterior
6	41	M	9	10	3900	− 6.4	7.25	Normal	Cef	Posterior
7	38 + 2	F	9	10	2910	NA	NA	Normal	Cef	Posterior
8	39	M	9	10	3470	− 4.5	7.23	Normal	Cef	Posterior

BGA birth gestational age, *BW* birth weight, *BE* base excess, *NE* neurological examination, *F. Pos* fetal position

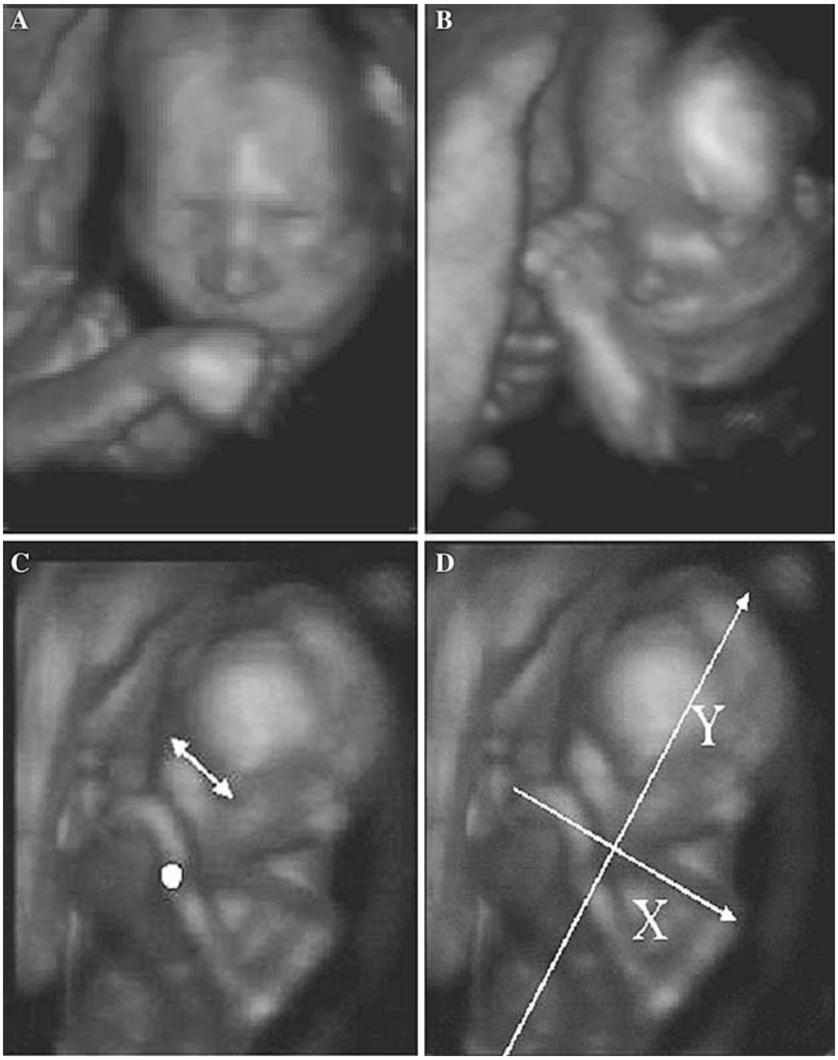

Fig. 1 Example of hand to mouth (**a**) and hand to eye (**b**) movements of the foetus at 22 weeks of gestation seen by 4D–US. **c** represents the intra-ocular distance and the position for the wrist marker. **d** represents the axes used to perform 2D kinematic analysis

foetal movements the transducer, which was maintained stationary, was positioned so that a frontal view of the foetus, including head, arms, hands, thorax and abdomen was obtained. Each foetus was taped for 20 min. The video recordings were then digitized through our purposely developed software which allows off-line kinematic analysis for hand to mouth and hand to eye movements.

Type of movements

Three types of arm movements were isolated and evaluated by three experts and were subsequently analyzed: (i) hand to mouth (Fig. 1a), when hand movements end at contact of finger with the mouth (ii) hand to eye (Fig. 1b), when movements end at contact of fingers with the eye; (iii) non-targeted movements, when movements were directed away from the body. These types of movements were discarded from analysis if one of the following conditions occurred: the foetus was not in a supine position or he/she was not clearly visible from the starting to the end point or if the head was rotated such as the eye position was not available. Therefore, only 30% of movements were actually considered (Table 3).

The occurrence of the analyzed movements at the considered gestational ages is reported in Table 3. Each foetus was analyzed by the same operator at all gestational ages. For obvious reasons it was not possible to ask participants to start from a precise loca-

Table 3 Number of analyzed movements directed to the mouth and the eye at the considered gestational ages

Gestational age (weeks)	Movements to the mouth	Movements to the eye
14	28	19
18	23	15
22	19	12

tion or at a specific command, thus the criteria for hand movements to begin was when the hand was stationary within the chest area (below the shoulders and above the belly). The criteria for "touched target" was when the hand clearly stopped on the mouth and eye areas. We took great care to discern target touch from proximity. Velocity change from zero was the threshold criteria for determining the start and end of the movement. Although many movements were detected only those that conformed to the above criteria were chosen for analysis within the 14–22 week gestational period. After the 22-week period, movements suitable for kinematic analysis become more difficult to identify. It has been shown that in pathological pregnancy the movement of the foetus can be influenced by amniotic fluid volume (Sival et al. 1990). Although in our studies we included only healthy pregnancies, we checked that the estimate of amniotic fluid was within the normal range (Table 2).

Kinematic analysis

Kinematic analysis of foetuses' spontaneous and unskilled upper limb movements presents formidable problems. In normal conditions, when kinematic analysis is performed, an absolute co-ordinates frame of reference that does not change in time is available. Importantly, anatomical landmarks may be referred to this frame of reference. By means of 4D ultrasonic technique it is not possible to define an absolute frame of reference in time, because the field of view of the transducer is continuously changing. Consequently, in the present experiment we had to consider a "foetus-centred" co-ordinates frame and refer all the performed movements to such a relative reference frame. Furthermore, anthropometric parameters change from one foetus to the other and within the same foetus at different gestational weeks poses additional problems. For this reason we could not adopt an absolute measurement unit (e.g., millimetres), but a relative measure, that is the intra-ocular distance (Reece et al. 1989; Tongsong et al. 1992). Further and most importantly, we had to consider the obvious lack of "co-operation" of the subject performing interesting movements. Thus, it was not possible to give "go" and "end" commands to the foetuses and it was not possible to control for the changes in foetus position in time given that it was not always possible to move the transducer to get a better view. Finally, kinematics had to be 2D because even if we were able to gain our data from 3D images, we could not perform a real 3D investigation. This is because the used instrument supplies only a 2D movie of the 3D acquisition and not digital 3D co-ordinates. Thus in order to capture both the dynamics of spontaneous movements and the properties of the reach itself the video recordings for these movements were imported into in-house software developed to perform 2D kinematic analysis. First, the video recording of the entire US session was imported. Second, relevant movements were identified by an expert analyst. Each experimenter analyzed all the moves and ANOVAs on the dependent measures of interest have been performed on the data. The results were similar for each experimenter. Furthermore, two independent viewers looked at each foetus's videoclips in order to control for possible discrepancies in the identification of the relevant movements. Both independent viewers confirmed that the data selected by the experimenters were correct. Third, each of the identified movements was classified taking into account the starting and ending area. Fourth, through a software procedure, the frame of reference, a measurement unit and an origin used to refer the examined body position were established. As mentioned above, in the case of 4D ultrasound images (3D images in time) it is not possible to define a priori frame of reference, thus we used the foetus himself. In particular, the origin of the frame of reference was the average point between the shoulders and measurement unit was the intra-ocular distance (see Fig. 1c). This procedure allowed us to compare the amplitude of the movements for different gestational ages. Intra-ocular distance is intimately related to head size and head size is commonly used to identify gestational ages (Tongsong et al. 1992). The next step was to assign the marker on the foetus's arm at wrist level (see Fig. 1c) and to track it frame by frame (frame duration, 100 ms) for the entire movement, with respect to the target zone (eye and mouth). The wrist marker was used to compute arm velocity (displacement derivative) and spatial trajectory data. This procedure was performed manually and post-hoc by the same analyst for all foetuses. Then, the movement was reconstructed considering the middle point between the shoulders as the frame of origin and line joining the shoulders as the horizontal axis (see Fig. 1d). The vertical axis was computed as the perpendicular of the horizontal axis given that kinematic analysis was performed in two-dimensions. Please note that for both trajectories and velocities profiles the spatial measurement unit is not an absolute measure. This means that unit measure of one does not refer to "1 mm" but to "1 intra-ocular distance". As a consequence, the obtained values are only meaningful within the subset of the analyzed foetuses.

Data analysis and dependent variables

The following dependent measures were calculated and analyzed. For the velocity profile we examined the percentage (%) of time spent from the beginning of the movement to peak velocity and the amplitude of peak velocity. For the spatial trajectories the length of the trajectories was considered. A repeated measures analysis of variance (ANOVA) with type of movement (mouth, eye) and period of gestation (14, 18, 22 weeks) as within foetuses factor was performed for movement duration and the velocity measures. Post hoc contrasts were carried out with Bonferroni corrections for multiple comparisons. Movements which were not goal-directed could not be included in the analysis, given that it was not possible to determine the end of movement (and consequently movement duration) and key kinematic landmarks (see Results).

While underlining that the combined results of the right and left hand movements are presented in this article, issues concerned with asymmetries are beyond the scope of this work.

Results

From a qualitative perspective, movements away from the body did not show any obvious kinematic patterning and differed greatly at all gestational ages from those which were goal-directed. For example, as shown in Fig. 2, the velocity profile for movements away from the body performed at 14 weeks gestation was clearly ballistic with three velocity peaks and with velocity which did not go back to zero. At 18 weeks velocity is maintained roughly constant and ends accelerating. At 22 weeks the velocity profile resembles that observed at 14 weeks but of lower amplitude. In particular, this pattern contrasts with the change in trajectory control noticed at 22 weeks for goal-directed movements (see below).

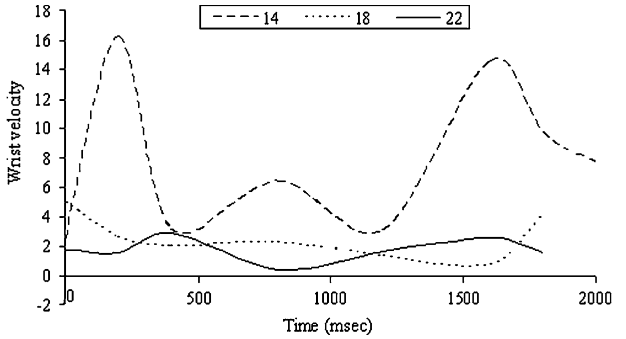

Fig. 2 Example of velocity profiles for a representative movement performed away from the body at 14, 18 and 22 weeks of gestational age. The measurement unit was intraocular distance

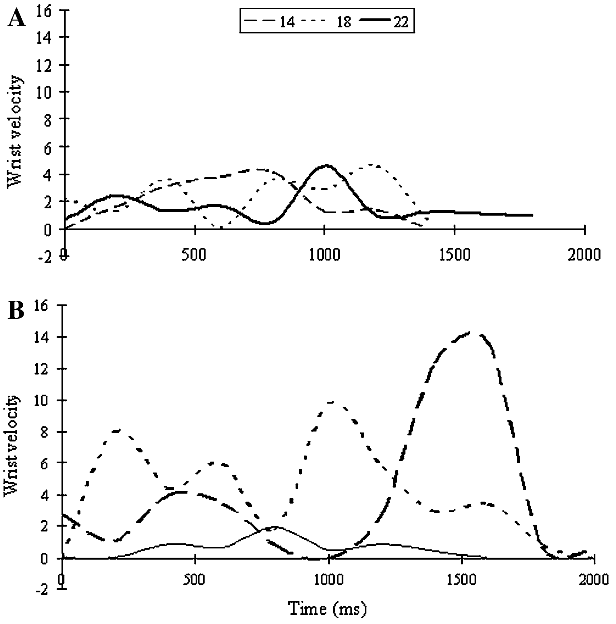

Fig. 3 Representative trajectory profiles for one representative movement of a foetus performed at three different gestational ages directed towards the mouth (**a**) and the eyes (**b**). The measurement unit was intraocular distance

The representative movements shown in Fig. 3a, b indicate that at 14 and 18 weeks gestation movements towards both the mouth and the eye were very jerky showing a zigzag kind of patterning. Exemplary, at 22 weeks the foetus showed an improvement in trajectory control which was confined to movements directed to the eyes. As represented in Fig. 4, at 22 weeks the amplitude of peak velocity for the movement directed towards the mouth (panel A) was higher than for the movement to the eyes (panel B). Further inspection of Fig. 4 indicates that at 14 and 18 weeks of gestation the velocity profile of this representative foetus for movements towards the eye (Fig. 4b) is characterised by a number of movement units that decrease noticeably at 22 weeks. Furthermore it can be noticed that at 22 weeks peak velocity for the movement towards the eyes (Fig. 4b) seems to be earlier and lower than that for the movement towards the mouth (Fig. 4a).

The results from the ANOVAs revealed a significant interaction between the main factor type of movement and age of gestation for all the considered dependent measures except for the length of the trajectory path: movement duration ($F_{1,21} = 18.21$, $P < 0.0001$); amplitude of peak velocity ($F_{1,21} = 43.32$, $P < 0.0001$); time to peak velocity ($F_{1,21} = 38.52$, $P < 0.0001$). Post hoc contrasts revealed that up to 18 weeks gestation there was no indication that the

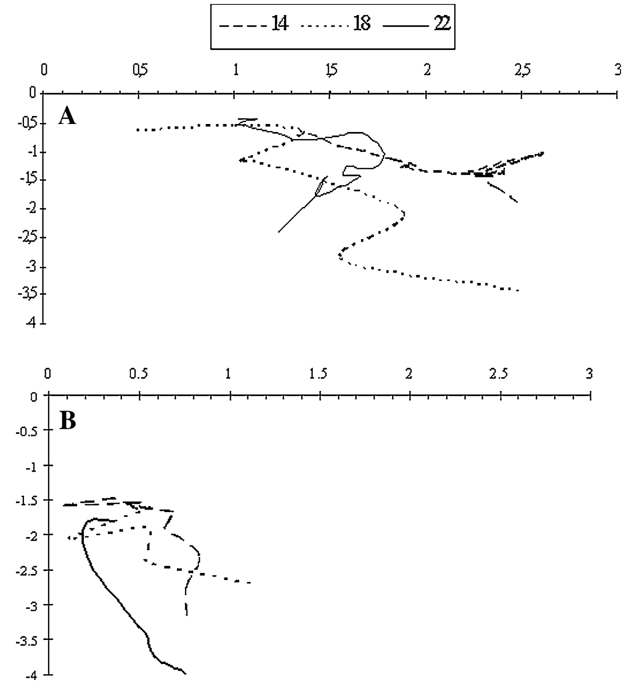

Fig. 4 Representative velocity profiles for one movement performed at 3 different gestational ages directed towards the mouth (**a**) and the eyes (**b**). The measurement unit was intraocular distance per second

eye, the smallest and most delicate of the two targets, was treated as a special kind of target object. For instance, as shown in Fig. 5a, movement duration was similar for movements to the mouth and the eye. Similarly, time to peak velocity (Fig. 5b) was reached at the same percentage of time for both types of movements. Importantly as shown in Table 4 this pattern applied to all foetuses.

In contrast, by 22 weeks of gestation, each individual foetus (Table 4) showed the expected movement duration and velocity patterning in terms of somatosensory properties of the target (Fig. 5a, b). For the mouth, movement duration was shorter (Fig. 5a; $P < 0.01$) and time to peak velocity was reached consistently later and it was higher than for movements directed towards the more delicate target (the eye; Fig. 5b; $P < 0.01$). Further the anticipation of peak velocity for the movements directed towards the eye resulted in a longer deceleration time.

The lack of significance for the interaction between type of movement and gestational age for the length of the trajectory path (Fig. 5c) seems to indicate that this parameter does not change across gestational ages. Importantly, even though at 22 weeks movement duration was longer for both movements to the mouth and the eye, the length of the trajectory was maintained constant as for the other two gestational ages. This may suggest (as evident from the qualitative analysis reported in Fig. 4) the use of straighter paths by 22 weeks.

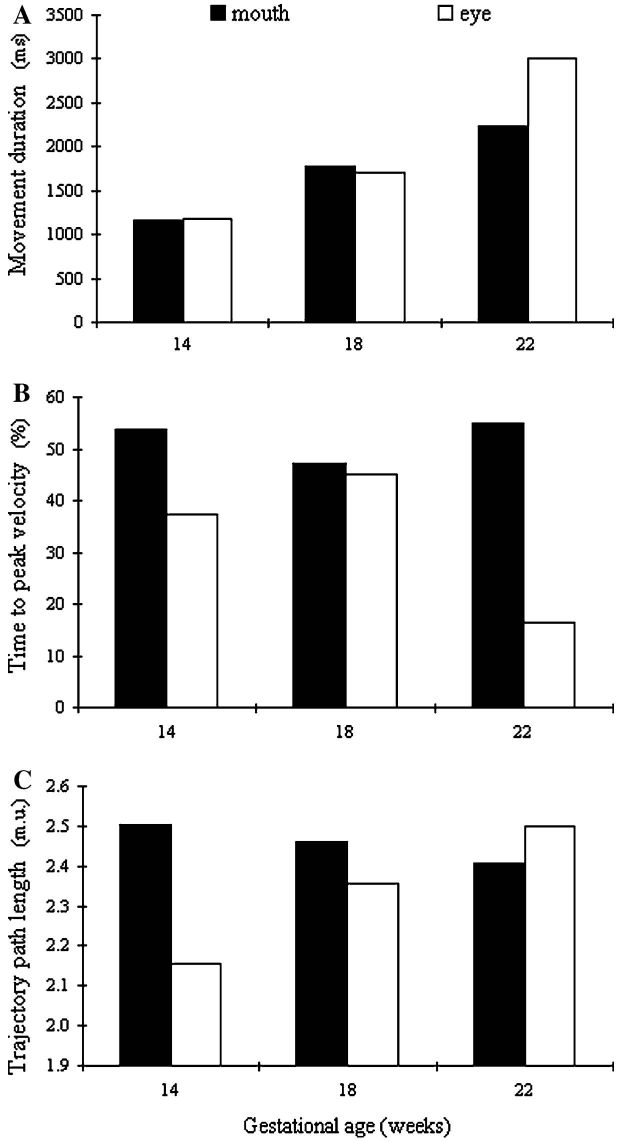

Fig. 5 Graphical representation of the interaction type of movement by period of gestation for movement duration (**a**), time to peak velocity expressed as a percentage of movement duration (**b**) and length of the trajectory path (**c**)

Discussion

The unique aspect of this study is that for the first time a kinematic approach is used to understand the movement dynamics of foetuses. The results of the off-line kinematic analyses for hand to mouth and hand to eye movements indicated that up to the gestational age of 18 weeks there was no evidence of coordinated

Table 4 Movement duration, time to peak velocity and trajectory path length for movement towards the mouth and the eyes at different gestational ages for each foetus

	Movement duration						Time to peak velocity (%)						Trajectory path length					
Gestational age	14		18		22		14		18		22		14		18		22	
	Mouth	Eyes	Mouth	Eyes	Mouth	Eyes	Mouth	Eyes	Mouth	Eyes	Mouth	Eyes	Mouth	Eyes	Mouth	Eyes	Mouth	Eyes
Fetus																		
1	1,700	1,600	3,000	2,850	2,700	2,900	60	37	52	77	56	35	2.1	2.1	1.4	2.4	2.5	2.6
2	1,400	1,400	1,600	1,550	2,000	2,800	48	36	49	43	50	36	2.2	1.9	2.6	2.3	2.4	2.5
3	900	1,000	1,200	1,150	1,600	3,200	54	36	48	34	56	20	2.4	2.2	2.7	2.5	2.3	2.5
4	1,900	1,850	2,600	2,550	2,700	3,300	47	36	48	38	52	14	2.4	2.2	2.8	2.5	2.4	2.5
5	1,100	1,200	2,400	2,300	3,000	3,200	62	38	46	32	50	22	2.7	2.5	2.8	2.3	2.5	2.3
6	1,100	1,000	1,000	1,000	1,600	2,800	52	45	46	38	53	23	2.3	1.7	2.5	1.9	2.1	2.6
7	900	900	800	900	1,800	3,200	45	40	47	50	56	12	2.6	1.8	2.1	2.5	2.5	2.5
8	900	850	1,700	1,800	1,600	2,800	47	35	45	48	50	10	1.8	1.8	2.7	2.6	2.7	2.4

kinematic patterns. Reaching was inaccurate and showed poor control of the hand trajectory with characteristics jerky and zigzag movements. However, by 22 weeks individual foetus reaching become straighter and more directly aimed towards the target. Importantly, acceleration and deceleration phases seem to be planned according to the size and/or delicacy of the target.

The present study is the first to report kinematic analyses over various gestational ages of some form of learning to reach in the foetus. Although previous qualitative studies reported that foetal hand movements did not appear to be random, but directed or aimed at specific targets (Sparling and Wilhelm 1993), they have not yielded such a consistent view of changing kinematic control. While we predicted that the foetuses would become better reachers, we were surprised by the noticeable change of kinematic patterning for the smaller, delicate target within the developmental course.

Good reaching means keeping the hand moving in a direct and smooth manner towards the desired target. By these criteria, new reachers are notoriously poor, but they improve considerably after several months of practice, as several previous studies have documented (von Hofsten 1991; Halverson 1931). Implicit in this previous work is that over time, infants gain better control of their limbs (Thelen et al. 1996).

In this article we have described changes in arm trajectory and velocity patterns in the foetus, probing more deeply into the nature of evolving arm control. In particular, the changes observed may suggest a primitive predictive process already operating in the foetus, in which the sensory consequences of a movement are anticipated and used to plan an action related to the nature of the target. The movement patterns we observed may indicate that information about the different sensations obtained by target organs is used to adjust the approach of the hand. By 22 weeks the fetus seems to “know” that the mouth is bigger and less delicate than the eye. By inference it could be suggested that the foetus has learned that the eye is a smaller and more delicate target, perhaps implying a concept of somatosensory sensitivity, by 22 weeks. Moreover, we found that faster movements were characterised by less straight trajectories and presented a greater number of submovements (though we acknowledge that for technical difficulties we were unable to perform a proper statistics on these observations). But how can the effects of object size/delicacy and movement speed on the kinematics of the foetuses be explained?

Object size and movement speed change the nature of the arm control problem. When people reach to a target not requiring a great deal of accuracy, they tend to be faster and do not pay much care to fine visual or proprioceptive corrections to their hand trajectories, and accuracy declines (Fitts 1954). Do we have here a foetus version of Fitt’s law, that is, a speed-accuracy trade-off, as previously reported in infants, children and adults? Although we cannot provide a definite answer to this question we feel that the pattern of data is sufficiently clear as to indicate that the reported effects are not casual. To date, the present results resemble in many aspects the pattern of results obtained in infant and children in which similar kinematics changes have been reported (e.g., Thelen et al. 1996; Newman et al. 2001).

There are however, some issues that need clarification before these conclusions can be fully accepted. The first issue is that if the foetus shows evidence of hand movement planning, then one would expect to see a continuity between foetal and newborn behaviour as it has been reported in other studies examining foetal behaviour in response to sensory probes such as vibroacustic and airborne stimuli (e.g., Kisilevsky and Muir 1991; DiPietro et al. 2002; Groome et al. 1999). Likewise, when comparing pre- and post-natal hand movements towards facial parts, an increase in such movements for the post-natal period has been reported (Sparling and Wilhelm 1993). On the other hand, as reported above, studies suggest that coordinated, intentional reaching is not observed in infants until about 3–4 months. Similarly, while hand to mouth movements occur in newborns, it is not until about 5–6 months that they become intentional (e.g., thumb sucking). Thus, if the movements being described in this paper are controlled by higher order processes (i.e., beyond brain stem) then one has to explain why they are not seen in the newborn. In this respect, it should be noted that measurement of changes in movement across the pre-post natal transition is rather difficult because of the difficulty in comparing the same movement in two totally different environments. Thus differences between the pre- and post-natal may stem from measures collected in different environments which encourage or restrain movements. Further, such differences could be explained from the "perturbation" from a viscous to a non-viscous and from a limited to an unlimited environment in which the infants then need to recalibrate. In this connection, we suggest that research emphasis may be best placed on developmental analysis that is environment specific. In other words, there might be an environment specific maturation process that cannot be maintained after birth.

Second, it could be argued that we are investigating a developing nervous system capable of spontaneous movements at a very early stage. Some of those movements will result in the stimulation of nociceptors, when they collide with delicate parts like the eye. Clearly this needs to be discouraged or the foetus will injure itself. Along these lines it could be said that it does not take a very sophisticated neural circuit to inhibit movements which may lead to self-injury. However, the risk of damage to an organ depends on a number of factors that will include the mass of the object approaching it and its speed. Considering that a foetus's hand is a very low mass travelling through a highly viscous medium of the amniotic fluid it could be argued that no real risks are involved. Thus, if the "risk" hypothesis can be discarded, then it might be reasonable to advance that the longer deceleration time (i.e., proportion of movement duration spent from peak velocity to the end of the movement) for a more delicate target object revealed at 22 weeks may provide evidence of movements which might not be haphazard or a reflex.

In this respect it is noteworthy to parallel the pattern noticed at 22 weeks for goal- and non-goal-directed movements. As shown in Fig. 2 movements which were not directed towards specific body parts do not show at 22 weeks any resemblance to those observed for the movements towards the eye or the mouth. This further strengthens the evidence of a possible proto planning process. Along these lines, it is of interest to parallel, with a certain degree of caution, the present results for goal- and non-goal-directed movements with recent studies suggesting differences in spontaneous arm movements in the presence or absence of a toy (Bhat et al. 2005; Bhat and Galloway 2006). In these studies, kinematic analysis revealed that when the toy was present, non-reaches altered the quantity of movements whereas near- and new-reaches altered the quality of their movement through spatio-temporal dissociation and reorientation of the arm (Bhat et al. 2005; Bhat and Galloway 2006). With caution it might be suggested that even at the foetal level it is possible to notice a differential pattern for goal- and non-goal directed actions which changes through gestational ages.

A final issue is concerned with the limitations applying to the present study. First, the necessity to set a strict protocol in terms of a comparable starting area and finishing area together with a comparable foetus position (head and shoulders have to be visible as to allow for the reconstruction of the co-ordinate system and the determination of measurement units) dictated a strict movement selection. Second, there were limitations concerned with spatial measurements precision. This was chiefly due to the measurement error related to the 3D/2D conversion of the acquired data. However, to partially mitigate this problem we discharged any movement performed perpendicularly to the observer's position. Further, we chiefly confined our analysis to time parameters (movement duration and maximum velocity time), which were not affected by errors due to the 3D/2D reconstruction. Reliability of time measurements was assured by four-dimensional ultrasound equipment.

It is important to highlight however, that our investigation was carried out in an unusual "laboratory" for standard motion analysis. Specific problems were dictated by the analysis of completely free movements in a completely free environment. Obviously it was not possible to set up any experimental protocol for our analysis, but we had to create a "measurement protocol" to compare the available data.

Despite the difficulties encountered in conducting this research, the precious data obtained suggest that arm movements in the foetus are more coordinated and complex than previously thought and that the psychomotor ability of the foetus might have been underestimated (Kisilevsky and Lowe 1998; DiPietro 2005; Groome et al. 1999; Kostović et al. 1995). This information is important for understanding the processes underlying the development of motor control and the maturation of the nervous system in general.

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